SEDIMENTARY PETROLOGY OF THE CARDIUM FORMATION, WEST-CENTRAL ALBERTA

By

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SEDIMENTARY PETROLOGY OF THE CARDIUM FORMATION, WEST-CENTRAL ALBERTA

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by

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ABSTRACT

Samples of the Cardium formation from the Pembina area and the Central Foothills belt of Alberta were examined in hand specimen and thin section. They were also analysed for clay mineral and heavy mineral content, and particle size distribution.

The main source of the clastic material was Mesozoic sedimentary rocks lying to the west of the Foothills belt in the vicinity of the present central and western Rocky Mountains. A relatively minor uplift in that area caused the retreat of the sea and produced the coarser clastic material. A secondary source was the metasedimentary and igneous rocks lying to the west of the present Rocky Mountain Trench in the vicinity of the Selkirk Mountains. A much more minor source was volcanism. The Pembina area may have had an additional source, probably to the north in the Peace River area.

Of special interest was the discovery of what is considered to be naturally etched, detrital spessartite garnet.

The Cardium formation at Pembina was deposited under relatively shallow water, wholly marine conditions, at times subject to wave action. This is shown by the excellent sorting (sorting coefficient of about 1.24) and the very fine-grained nature of the deposit.

Subsequent to deposition, there was some circulation of intrastratal solutions which etched the garnet, deposited the silica cement and may have removed some accessory heavy minerals from the Foothills Cardium. Involvement in the Rocky Mountain uplift caused reversal of the original dip.

ACKNOWLEDGMENTS

The samples used in this study came from three oil well cores in the Pembina field and from six outcrop locations in the Central Foothills. The cores were kindly lent by Mobil Oil of Canada and Pan American Petroleum Corporation, whose cooperation is gratefully acknowledged. All but one of the outcrop samples were collected in the summers of 1957 and 1958 by Dr. J. F. Lerbekmo. The other sample was obtained from a collection in the Department of Geology.

This investigation was largely made possible by a Fellowship from the Shell Oil Company held by the author during the winter 1958-59. The writer also wishes to acknowledge the help and facilities provided by Imperial Oil Limited during the summer of 1959.

The staff of the Department of Geology at the University of Alberta critically read the manuscript. In particular, the author wishes to acknowledge the help and encouragement of Dr. J. F. Lerbekmo. Dr. F. A. Campbell assisted with the identification of the garnet. The Geological Division of the Alberta Research Council did the X-ray analysis of the clay mounts.

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CHAPTER I

INTRODUCTION

General Statement

The Cardium formation (Upper Cretaceous) outcrops in a narrow band in the Foothills belt of western Alberta from near the 49th parallel northwest to the Peace River block of Alberta and British Columbia. In subsurface, the formation extends eastward under the plains some distance before it shales out. This distance is variable and about the most easterly point reached is Edmonton.

Under the plains, the formation is almost flat-lying and dips slightly to the west. Going westward, this dip becomes more pronounced. In the foothills, the formation is involved in Foothills structures, is often faulted, and shows very steep dips to the west and to the east.

The discovery of oil in the Cardium formation in the Pembina area in 1953 aroused a great deal of interest in this formation.

Since the amount of recoverable oil is related to the thickness, porosity and permeability of the sandstone horizons, the studies carried out by the oil companies have been largely to determine these characteristics of the sandstones and their effect on the economic limits of the field. To this end, core examination and electric log study have been most strongly relied upon. The limits of the field have now been fairly well delineated.

The purpose of the investigation was to try to determine the provenance, depositional environment, and diagenetic history of the Cardium formation and to relate these to the presence of an oil reservoir at Pembina. To this end, a petrological study, including

mechanical analysis, heavy mineral analysis, clay analysis, and thin-section study of the formation both at Pembina and in the Central Foothills, has been undertaken.

Previous Work and History of the Formation Name

There has been a great deal written on the Cardium formation, mostly in connection with mapping of areas in the Foothills. Since 1953 the literature includes much written by oil company geologists on the Cardium in subsurface.

The term Cardium was introduced as a rock unit name by Dr. Hector, a member of the Palliser Expedition to the Canadian West in the years 1857-60, when he applied it to a series of shales and sandstones along the Bow River. The name was applied because of the abundance of the fossil *Cardium pauperculum* in the shale-sandstone series (Harris, 1954). In 1907 Cairnes, of the Geological Survey of Canada, while mapping in the southern Foothills, restricted the use of the name Cardium to the predominantly sandstone part of the shale-sandstone sequence (Cairnes, 1907). G.S. Malloch (1911), also of the Survey, in his memoir on the Bighorn coal basin of west-central Alberta, named a formation with similar lithology and fauna to the Cardium formation, the Bighorn formation. He correlated it with the Cardium formation to the south. Since that time both names have been used almost interchangeably. By and large, the Survey has kept "Bighorn" and the oil industry "Cardium", with "Cardium" gradually supplanting "Bighorn". Unfortunately, neither name is well chosen, since Bighorn is used for a formation in Wyoming, which has precedence, and Cardium is named after a fossil, which is, strictly speaking, not admissible. The fossil is not

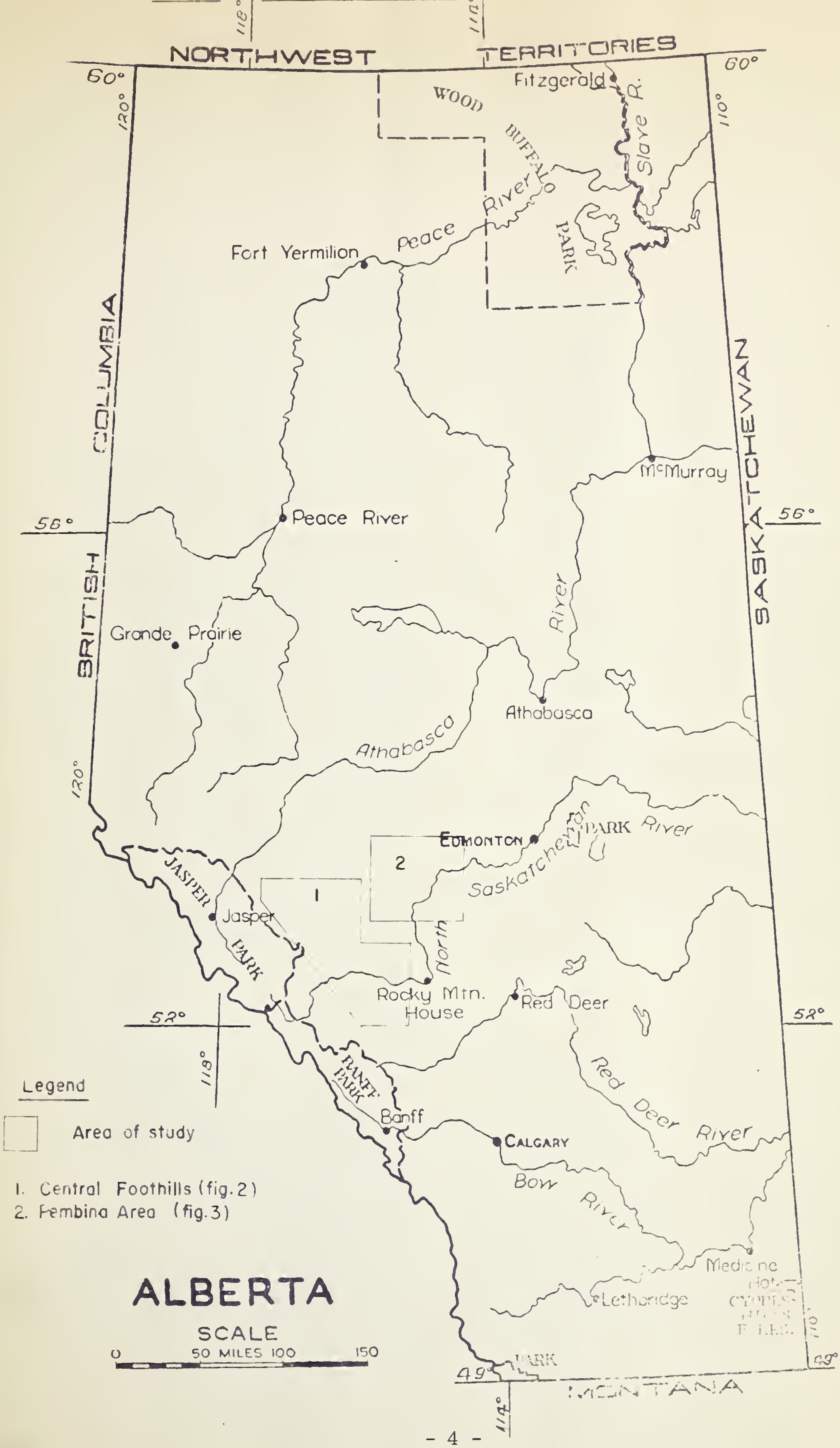
restricted to the formation, nor is it particularly abundant in the formation.

In the area of the Foothills discussed in this investigation (Figs. 1 and 3) geological mapping has been done by both the federal and provincial governments. In most cases only a general description of the formation, a detailed section typical of the area and details of fossils, if any, are given. However, Allan and Rutherford (1924) did some petrographic work and from this drew some conclusions concerning the source and depositional environment of the sediments of the formation.

In the Pembina area a great deal of work has been done within the last four years by the oil companies and some has been published. There has been some controversy about whether the formation is a turbidity current deposit. Beach (1955) was the first to raise the question and later (1956) defended it. Some of those against this origin were DeWiel (1956), Nielsen (1957), Michaelis (1957) and Mountjoy (1957).

Some study of the heavy minerals in the Cardium formation has previously been undertaken at the University of Alberta (Patton, 1955, and Beveridge, 1956).

Figure 1 Index Map of Alberta



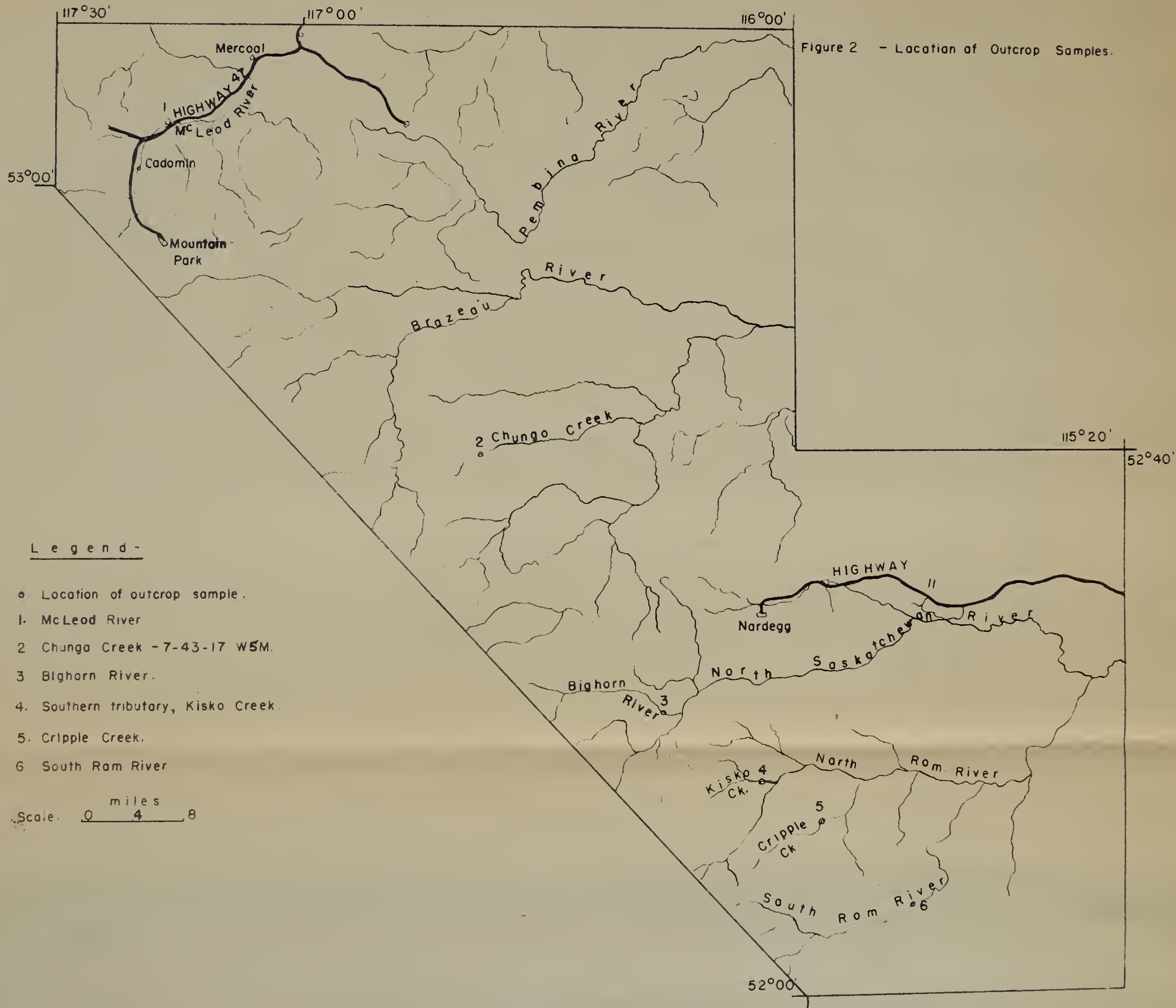
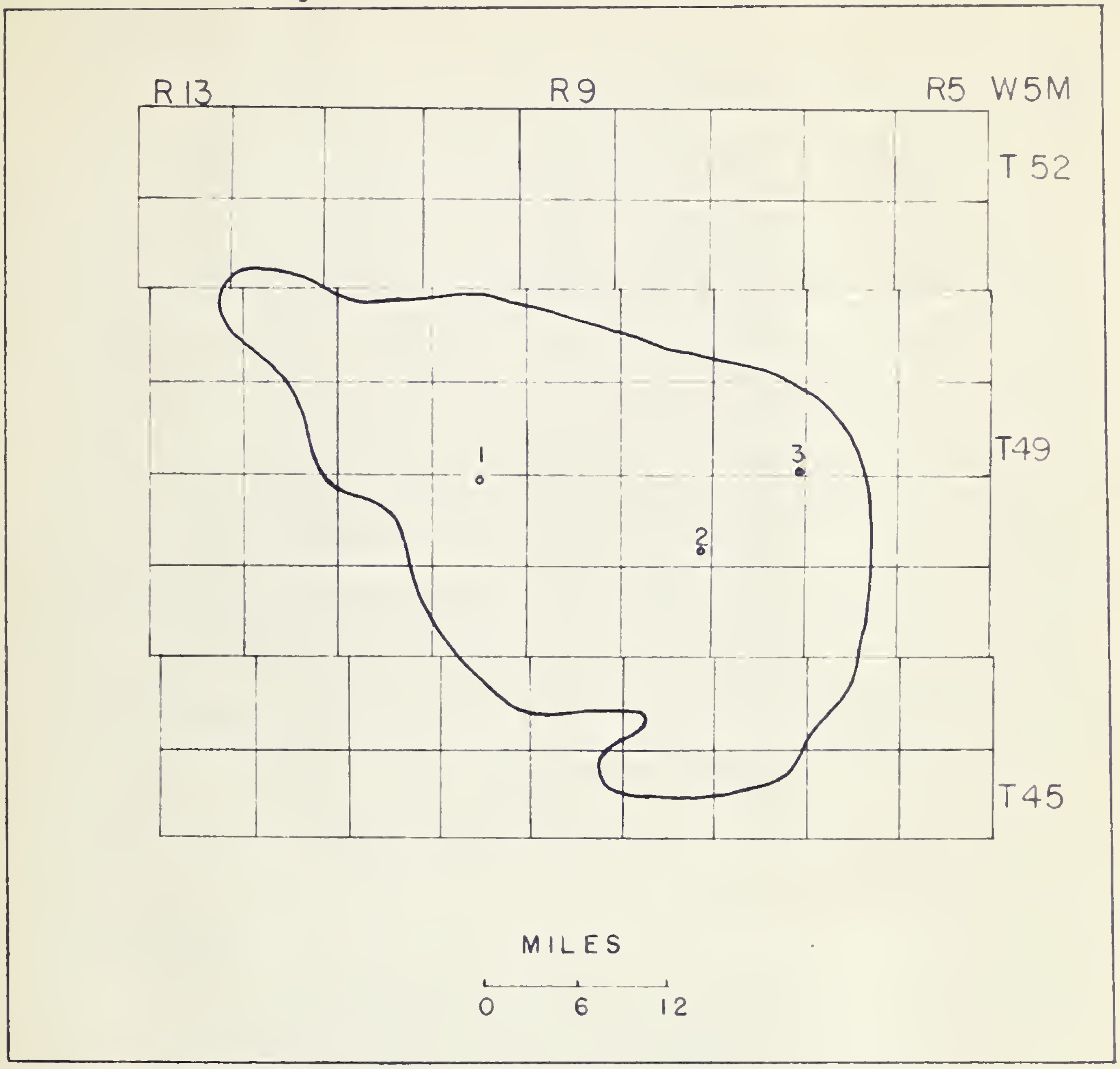


Figure 2 - Location of Outcrop Samples.

Figure 3 Location of Wells in Pembina Field



Legend

- ° Well used in study
1. Stanolind Hudson's Bay Rat Creek B-12
2. Socony Seaboard Pembina 1-10
3. Mobil Oil Seaboard Drayton Valley 1-12

— Outline of Pembina Field (after Patterson and Arneson, 1957, p. 945)

CHAPTER II

STRATIGRAPHY

General Statement

The Cardium formation is Upper Cretaceous in age, belonging to the uppermost Turonian stage with the upper part belonging possibly to the lowermost Coniacian stage (Stelck, 1955). It conformably overlies the Blackstone (Lower Alberta) marine shale and is conformably overlain by the Wapiabi (Upper Alberta) marine shale. The formation thickens to the west and pinches or 'shales' out in the Edmonton area, where it is lost as a marker horizon.

This relatively thin sandstone formation in a dominantly marine shale sequence was evidently deposited during a short but abrupt uplift which considerably shallowed the Blackstone sea in the Foothills and surrounding area. Cardium deposition ended when an extensive advance of the sea returned conditions essentially to what they were during Blackstone time.

Foothills

In the Foothills the Cardium formation is composed of three sandstone members (locally two or four) about 35 feet thick, separated by relatively thicker, 50 to 100 feet, black shale members, the shale resembling that of the Blackstone and Wapiabi formations. The sandstone is hard, laminated, thick-bedded, platy to massive, fine to coarse grained, quartzose, and well sorted with subrounded grains. Locally it may be siliceous, calcareous and/or iron-stained and often shows cross-stratification. At least one, and

often more, of the sandstone members is capped by a bed of pebble conglomerate which is of variable thickness but averages about two feet in thickness. The pebbles are well rounded quartzites, and varicoloured cherts set in a sand matrix. The diameter of the pebbles varies but is generally about three-quarters of an inch. Pebble size increases to the north in the Peace River area, as does the average thickness of the conglomerate beds. In the Central Foothills several very thin impure coal beds have been found in the upper sandstone member of the Cardium formation, which may indicate that part of the present Foothills was the site of, or was very near to, the western shoreline of the sea at that time (Allan and Rutherford, 1924; Rutherford, 1925). In this area the Cardium formation is 250-300 feet thick with the sandstone members from 25 to 50 feet thick. South of Banff it is slightly thinner and thins appreciably south of the Bow River (Cairnes, 1907). North of Jasper it thickens considerably, reaching a thickness of 500 feet or more (Irish, 1951).

Pembina Area

In the Pembina area (Fig. 2), some 80 miles to the east of the Central Foothills, the Cardium formation has a somewhat different character than in the Foothills.

A conglomerate bed, usually a foot or so thick but occasionally more, made up of varicoloured chert pebbles, marks the boundary between the Cardium and Wapiabi formations. This is known in the oil industry as the 'Zone top' (Patterson and Arneson, 1957). Beneath the conglomerate is 55-90 feet of dark-grey, carbonaceous, pyritic shale, known as the 'upper shale member' (Chart 1). This

shale grades directly into another conglomerate bed very similar to the upper one. This conglomerate is composed of varicoloured chert and quartz pebbles up to three or four inches in diameter (Mountjoy, 1957) set in a matrix which grades downward from mudstone to sand or silt. Occasionally a sandstone pebble is found, the sandstone being similar to that underlying the conglomerate. Commonly, parts of the conglomerate are cemented with sideritic mudstone or ironstone. In one core examined (Drayton Valley 1-12) some reversed graded bedding appeared to be present in the conglomerate. The pebbles became coarser toward the top and there are two fairly distinct layers present. The conglomerate is of variable thickness, 0 to 20 feet, and it is thought it may be related to submarine topography (Nielsen, 1957). In some areas of the field the conglomerate has no fine matrix and is oil-bearing, but this is not common.

Below the conglomerate there may be a thin bed (six inches or so) of black shale as above, but more often it lies directly on the 'upper sandstone member' of the producing sands. In many places the conglomerate rests on what appears to be a scour or erosion surface which probably indicates a slight depositional hiatus (Plate 6, Fig. 2).

The 'upper sandstone member' is the main oil producing horizon of the two, and occasionally three, present. It is a quartzose sandstone, very fine to fine grained, subangular to subrounded, very well sorted, clean, often cross-bedded, invariably oil-stained and occasionally calcareous and/or siliceous. It has a measurable porosity of about 18 per cent with a maximum of 28.9 per cent (Parsons, 1955). Below the sandstone occurs

Chart 1

Correlation Chart, Nordegg Area - Pembina Area

	Nordegg Area, Chungo Creek (modified after Peterson and Labrecque, 1958, p.21)		Pembina Field, Discovery Area
	Wapiabi formation		Wapiabi formation
Cardium formation	chert pebble cgl., 6" - 1'		"Zone Top", chert pebble cgl., 2' ±
Cardium formation	sandstone, 10' shale, minor sandstone near top, 108' siltstone, 20' shale, minor sandstone, 62'		'upper shale member', 55' - 90' chert pebble cgl., 0 - 20'
Cardium formation	sandstone, 62'	'Producing zone'	'upper sandstone member', 25' ± 'middle member', 15' ± 'lower sandstone member', 15' ±
Cardium formation			'lower shale member', 50' ±
	Blackstone formation		Blackstone formation

a middle unit known in some parts of the field as the 'middle tight member' (Nielsen, 1957). In many parts of the field it is non-producing where it is composed of complexly interlensed sandstone and shale. In other parts of the field, however, a porous sandstone does develop in the upper part of the unit and it becomes an oil reservoir. Below the 'middle member' occurs the 'lower sandstone member' which completes the 'producing zone' at Pembina. This sandstone is very similar to that of the upper sandstone unit. However, it is not as thick nor as continuous as the 'upper sandstone member' and is broken up by numerous shale lenses. The lower sandstone grades into the 'lower shale member', which is about 50 feet thick.

In the discovery area of the field, the 'upper sandstone member' is about 25 feet thick and the 'lower sandstone member' 12 - 15 feet thick. The 'middle member' is about 15 feet thick. This gives the 'producing zone' a thickness of 50 - 55 feet. These thicknesses vary considerably over the field, though, so that in some places the 'upper sandstone member' is only 5 - 8 feet thick.

On the basis of facies changes in the three 'members' of the 'producing zone', Nielsen (1957) divided the field into four areas, which are:

I. A strip about four miles wide in the centre of the field which expands in the southern part to take in the south-eastern corner of the field. This was the original discovery area. In this part the upper and lower sandstones are separated by the 'middle tight member'. This could be regarded as the

south, so that at Pembina it is probably only a diastem. The conglomerate at the top of the 'Cardium Zone' at Pembina is correlative to the Baytree conglomerate in time and may represent a final minor uplift to the west before the sea advanced (C.R. Stelck, personal communication).

CHAPTER III

PARTICLE SIZE COMPOSITION

Methods of Analysis

Samples for mechanical analysis were selected from cores only, since it was felt that the outcrop samples would be too hard to break up without breaking the grains.

Eighteen samples from the three cores (seven from Pembina 1-10, five from Drayton Valley 1-12, and six from Rat Creek B-12, see Appendix for sample locations) were selected from single sedimentation units of sand. The pieces of core selected were halved lengthwise and one-half used for the analysis. The samples were broken into pieces about one-half inch across and disaggregated by use of a buckingboard and muller. On small pieces the muller is quite efficient and yet gentle enough not to break individual grains if care is taken not to prolong the treatment unduly.

Care was taken to see that the material being crushed was sieved often so that the finer material was not subjected to any more grinding than necessary. The crushed material was then sieved on a Ro-Tap sieve shaker for 10 minutes. The sieve numbers used were 80, 100, 120, 140, 170, 200, 230, 270, and, in some cases, 325-mesh of the U.S. Standard series. The material retained by the coarser screens was examined under a stereo-microscope to determine whether the particles were individual grains or aggregates. Most of the material coarser than 140-mesh in the first sieving was made up of composite particles. This material was taken out, crushed as gently as possible with a mortar and pestle, and re-

sieved. The procedure was repeated as often as necessary until the grains were all single particles.

Pipette analyses, to determine the silt and clay content, were run on only three samples, Pembina 1-10-C, D and F, and the values plotted on the cumulative frequency curve of each. This is a very time-consuming process and it was felt that the results obtained would not justify the further time required, since in all but two other cases the silt and clay fractions made up less than ten per cent of the sample.

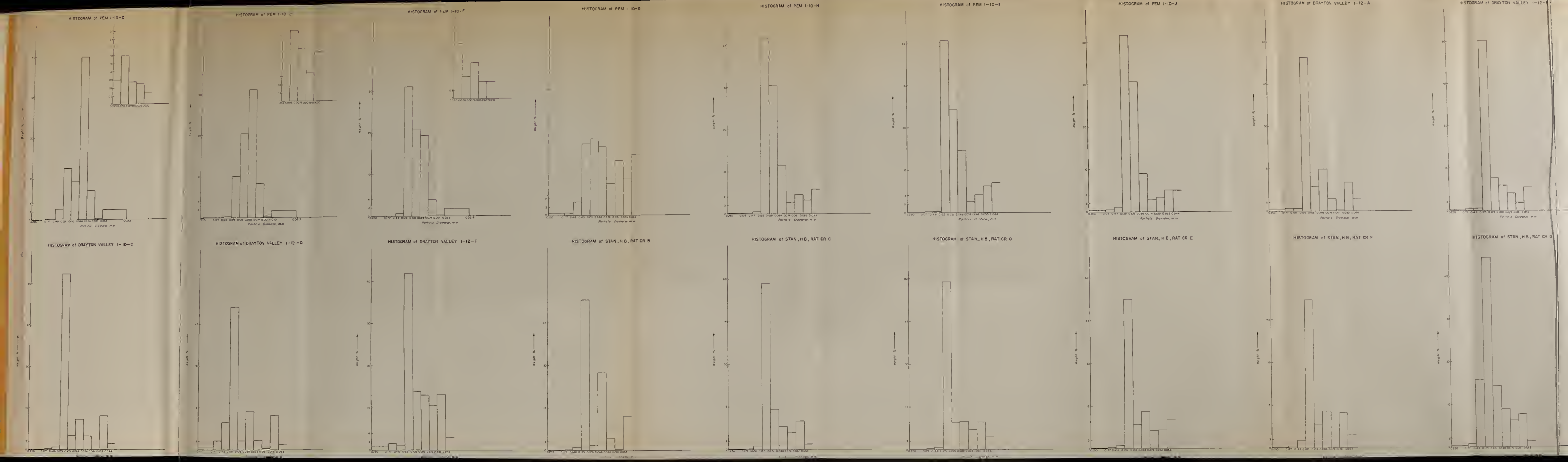
Significance of Results

The results of the mechanical analyses are shown by cumulative frequency curves (Appendix E) and in histograms (Fig. 4). The median (M) and the quartiles (Q_1 and Q_3), or the 75th and 25th percentiles, were read off the curves and the coefficient or sorting, So ($\sqrt{\frac{Q_3}{Q_1}}$) and the quartile skewness Sk ($\frac{Q_1 \cdot Q_3}{M^2}$) calculated. The results, along with the modes from the histograms and the percentages of sand size material, were put in table form (Table 1). This table shows a considerable degree of similarity between the samples.

The histograms of the samples (Fig. 4) show that all, with the possible exception of D.V. 1-12-B, are polymodal. Twelve are bimodal and the remaining six are trimodal. In fifteen of the samples the principal mode is 0.115 mm, where it is four to six times as great as the secondary mode. This size appears as a secondary mode in one of the remaining three samples, so that it is absent in only two samples. A secondary mode occurs in the finer sand class in half of the samples, while a secondary or

FIGURE 4

Histograms from mechanical analyses
of well samples.


HISTOGRAM of PEM 1-10-C
HISTOGRAM of PEM 1-10-D
HISTOGRAM of PEM 1-10-F
HISTOGRAM of PEM 1-10-G
HISTOGRAM of PEM 1-10-H
HISTOGRAM of PEM 1-10-I
HISTOGRAM of PEM 1-10-J
HISTOGRAM of DRAYTON VALLEY 1-12-A
HISTOGRAM of DRAYTON VALLEY 1-12-B
HISTOGRAM of DRAYTON VALLEY 1-12-C
HISTOGRAM of DRAYTON VALLEY 1-12-D
HISTOGRAM of DRAYTON VALLEY 1-12-F
HISTOGRAM of STAN, H B, RAT CR B
HISTOGRAM of STAN, H B, RAT CR C
HISTOGRAM of STAN, H B, RAT CR D
HISTOGRAM of STAN, H B, RAT CR E
HISTOGRAM of STAN, H B, RAT CR F
HISTOGRAM of STAN, H B, RAT CR G
Weight %
Particle Diameter, mm

tertiary mode occurs in the coarse silt class in all but one of the samples.

According to Pettijohn (1957, pp. 35, 44-46), "... bimodal distributions are rather common ..." but perhaps are more common in the coarse grained sediments such as alluvial gravels. Their cause or causes, though, are not well understood. An obvious cause could be faulty sieving technique, but since all the samples are similar and each was examined while sieving, this seems unlikely. The sieves were checked numerous times and they were all intact each time. Similarly, it could be caused by sampling two or more different strata. This may be at least part of the explanation since most of the samples contained varying numbers of shale micro-laminae. Whether this would account for all the observed bimodality is not known. Several other explanations can be offered, one being that the depositional site was receiving sediment from two or more sources which were incompletely mixed prior to deposition. Another possibility is that the bimodality is caused by differential sorting, one relatively fine size grade being carried away in preference to others. It seems possible that both of the latter conditions could have been operative. Samples P.1-10-C, D and G have primary modes finer than 0.115 and so may have had a different depositional history than the others.

The likeliest explanation of all for the bimodality is that the sieves used were too close together in size. The tolerance for new A.S.T.M. is about six per cent of the sieve opening. This is from one-third to one-half the difference between sieves. Since the sieves were not new, this tolerance may have increased, cutting down the difference even more. As a check, the data was replotted

using only every fourth sieve size and the curves produced were normal.

The coefficient of sorting measures the spread of the frequency distribution curve of a sediment. Trask (1932, p. 72) defines a well-sorted sediment as one with an So value less than 2.5, a normally-sorted one with a value of about 3.0 and a poorly-sorted one with a value of greater than 4.5. Sorting is one measure of the maturity of a clastic sediment. In general, the better sorted the sediment is, the more mature it is.

The sorting coefficients of the samples analysed show that they fall within the well-sorted class. This suggests that the sediments are relatively mature. The upper four samples of Pembina 1-10 are not so well sorted as the others.

Skewness is a measure of the predominance of coarse or fine admixtures in the sediment. Values less than 1.0 mean a predominance of fine material, while values greater than 1.0 mean a predominance of coarse. All the quartile skewness values obtained are less than 1.0, showing the sediments are skewed (slightly in most cases) toward the fine.

The median diameters of the samples are quite similar, especially those from Drayton Valley 1-12 and the Rat Creek well. Those from Pembina 1-10 are smaller than the others. In addition, the upper four are finer than the lower three.

As might be expected, there seems to be a definite, although not always consistent, relationship between median diameter, coefficient of sorting, skewness and the percentage of sand size material in any one sample. The amount of sand size is the independent variable with the other sizes dependent on it. The coefficient of sorting is particularly sensitive to the amount of sand size

Table 1

Data from Mechanical Analyses

Sample		Median, mm.	Modes* mm.	Coefficient of sorting So	Skewness Sk	Per cent sand size material (> 1/16 mm)
Pem. 1-10	C	0.079	0.115 (2) 0.081 (1) 0.041 (3)	1.34	0.68	71.42
	D	0.079	0.081 (1) 0.041 (2)	1.45	0.67	70.01
	F	0.090	0.115 (1) 0.041 (2)	1.35	0.85	75.79
	G	0.079	0.097 (1) 0.057 (2)	1.37	0.89	63.84
	H	0.100	0.115 (1) 0.057 (2)	1.16	0.97	86.66
	I	0.098	0.115 (1) 0.049 (2)	1.20	0.93	82.68
	J	0.101	0.115 (1) 0.049 (2)	1.14	0.99	86.54
D.V. 1-12	A	0.108	0.115 (1) 0.081 (2) 0.049 (3)	1.21	0.80	85.30
	B	0.108	0.115 (1) 0.049 (2)**	1.17	0.86	88.95
	C	0.109	0.115 (1) 0.081 (2) 0.049 (3)	1.20	0.80	85.58
	D	0.111	0.115 (1) 0.081 (2) 0.049 (3)	1.22	0.80	85.44
	F	0.101	0.115 (1) 0.057 (2)	1.27	0.81	83.89
Rat Ck.B-12	B	0.106	0.115 (1) 0.081 (2) 0.049 (3)**	1.22	0.81	87.86
	C	0.107	0.115 (1) 0.057 (2)	1.17	0.88	88.01
	D	0.108	0.115 (1) 0.057 (2)	1.22	0.73	86.16
	E	0.106	0.115 (1) 0.081 (2)	1.22	0.81	84.35
	F	0.108	0.115 (1) 0.081 (2) 0.057 (3)	1.24	0.77	83.43
	G	0.110	0.115 (1) 0.057 (2)	1.17	0.90	91.00

* Numerals after the modes indicate primary, secondary, etc.

** Probable modes

material, small increases in the latter producing small, but noticeable, decreases in the coefficient. According to Pettijohn (1957, p. 42) median diameter, coefficient of sorting and skewness are "theoretically wholly independent," although he goes on to say that in actual fact this is not the case. It is shown for these samples that, while they are not directly related, they are indirectly related through their dependence on the percentage of sand size material.

Inman (1949, p. 67) states that, in general, "sediments with median diameters near the grade of fine sand are the best sorted, sediments coarser and finer are more poorly sorted." The values obtained here give some support to this statement. Griffiths (1952), in a study of the characteristics of oil-reservoir sandstones, has shown that there is a relationship between median diameter and the presence or absence of oil in a rock. He states that oil-reservoir rocks are principally confined to sands with average sizes in the fine to very fine sands. He sets the upper limit for the median at about 0.250 mm. and the lower at the sand-silt break. Sediments with median diameters above and below these limits seldom contain oil. He also states that oil-reservoir sands are among the best sorted sediments. Thus, sands are potential oil-reservoirs if they fall within the size limits postulated by Griffiths, since Inman has shown that sediments of this size are the best sorted. The Cardium oil-sands conform to this relationship between sorting, median diameter, and the presence or absence of oil.

CHAPTER IV

PETROGRAPHY

Heavy Mineral Study

A study of the heavy accessory minerals was undertaken on a total of fifty samples, thirty-six from the Pembina area and fourteen from the Central Foothills. The locations are given in Appendix C. Each sample was disaggregated and sieved, the 80 to 270 mesh fraction being retained for separation in tetrabromoethane (S.G. = 2.9). The large size limits were used in order to obtain as representative a selection of heavy minerals as possible. The sieved sample was weighed, poured into tetrabromoethane in a separatory funnel and stirred vigourously. The heavy minerals (S.G. $>$ 2.9) sank to the bottom of the funnel and were drawn off into a filter paper-lined funnel. The residue was drawn off into a second lined funnel. Both fractions were washed with acetone and dried under vacuum.

Any magnetite and iron-filings in each heavy mineral fraction were removed with a hand-magnet and the resulting fraction weighed. The weight per cent of heavy minerals in each sample was calculated. A representative fraction of each heavy mineral sample was obtained by use of a microsplit and mounted in Aroclor (n = 1.66). All the slides were examined microscopically using both reflected and transmitted light and eighteen were used for statistical counts of different mineral species.

The results of the counts are presented in Table 2. The percentages of non-opaque and opaque minerals were independently calculated but the percentages of each in the slide are given.

Table 2

Frequency Distribution of Heavy Minerals

Sample Number	Apatite	Biotite: brown, red-brown	Biotite: green	Chloritoid	Collophane	Corundum	Diopside	Garnet: etched	Garnet: pitted	Garnet: 'normal' detrital	Hornblende	Muscovite	Rutile	Siderite	Spinel	Tourmaline: very well rounded	Tourmaline: subrounded, subhedral	Tourmaline: angular, irregular	Tourmaline: angular, euhedral	Zircon: very well rounded	Zircon: subrounded, subhedral	Zircon: angular, irregular	Zircon: angular, euhedral	Opaques: Hematite	Opaques: Ilmenite	Opaques: Leucoxene	Opaques: Pyrite	% Total opaques	% Total non-opaques
D.V.1-12-A	5	6	3	4	3					3		2	2	2		6	4	2		3		2			8	6	7	30	70
D.V.1-12-D	5	4	2	3					6	3		2	3	5		5	2			5	2				4	2	9	56	44
D.V.1-12-H	3	2		2					6	2		1	5			3	1			8	2	1			7	5	8	22	78
D.V.1-12-K	2	2	2	2					5	2		2	4		2	3	2			8	2		2		9		6	11	89
P.1-10-A						8										7				5					2		9	96	4
P.1-10-D	6	4	3	5			3	4					3		3	3	3			5	4		4			2	9	85	15
P.1-10-H	4	2	2	4	1		2	4		1	2	3	2	5	2	7	4	1	1	4	2	1	1		8	6	7	16	84
P.1-10-J	4	2		2	2			3					4	2	2	3	3			8	3	2	2		3	2	9	50	50
P.1-10-M	3	2	2	2	2		1	5			2	2	4			3	2			8	3	2	2		6	5	8	8	92
P.1-10-R	3	2	3	4				3			2	2	4		2	5	3			8	3				7	8	7	17	83
Stan.H.B.Rat Cr.B.	7	4		4				1				2	4		2	6	4			5	4	2			8	7		13	87
Stan.H.B.Rat Cr.F.	5	3	3	3	2				2	1		4	3	3	2	6	2			7	2	3	2		3	2	9	62	38
Stan.H.B.Rat Cr. I.	6	5	3	4					2			3	3	2	2	6	4			6	2	2			8	6	6	10	90
#2952	3	7	5	2	2					2		4	2			6	3			4	2			6	8	6	5	23	77
#2953	4	6	5	4	1		1			2		4	5			4	2			5	3				8	6	7	11	89
#2954	2	6	3							2			2	5		7	3			5	2			7	7		8	39	61
#2955	2	3	4		2					2	1	3	2	8		4	2			6	2				8	7		21	79

East

West

Legend:

1 = <1%
2 = 1-3
3 = 3-6
4 = 6-9
5 = 10-15%
6 = 15-25
7 = 25-40
8 = 40-70
9 = >70%

For several slides, P.1-10-A and D, the predominance of opaque grains over non-opaque was so great that less than fifty non-opaque grains were counted. While the results of the counts are tabulated for these, they probably are not very significant.

Photomicrographs of some of the heavy minerals present are shown in Plates 1 to 5.

The following heavy accessory minerals were noted.

Non-Opaque		Opaque
Apatite	Rutile	Hematite
Biotite	Siderite	Ilmenite
Chloritoid	Spinel	Leucoxene
Collophane	Topaz	Pyrite
Corundum	Tourmaline	
Diopside	Volcanic Glass	
Epidote	Zircon	
Garnet	Zoisite	
Hornblende	Unidentified	
Muscovite		

Tentative identification of andalusite and sphene has also been made.

Description of Non-Opaque Heavy Minerals

Apatite

Apatite is present in every sample, except P.1-10-A but appears to be more common in the Pembina samples than those from the Foothills. The grains are usually colourless, although some have purple cores (Plate 2, Fig. 1). These cores may be iron oxide as those grains

with them come out at a lower magnetic setting than the colourless grains. Most of the grains are rounded to well rounded, some being egg-shaped or nearly circular. Some grains are subangular to subrounded. Of these, most are subhedral or euhedral, a few being irregular. The subhedral and euhedral grains show a prismatic or tabular habit. These grains are likely first-cycle while the more rounded ones are multi-cycle. A few grains show rod-like inclusions oriented parallel to the long axis of the grain.

Biotite

Biotite is present in every sample, in several being the most abundant species. It appears to be more abundant in the Foothills samples than those from Pembina. It occurs as fairly large, subrounded to rounded flakes, lying on the basal pinacoid. The flakes are of both the brown and green variety, while some are deep red-brown which may represent alteration. Usually, the brown variety predominates over the green. Some grains have numerous black, needle-like inclusions (iron-oxide) oriented semi-parallel to each other.

Chloritoid

Chloritoid is a fairly common mineral, being present in nearly every sample. It is less common in the Foothills samples. The grains are usually subrounded and may be first-cycle.

Collophane

Collophane is not present in all of the samples and when present rarely exceeds one or two per cent of the non-opaque minerals. It appears to be somewhat more consistently present in

the Foothills samples than the well samples. It is identified by its yellow-brown to dark brown colour and speckled appearance under plane polarized light and isotropic, or weakly anisotropic, character under crossed nicols. The grains are subangular to subrounded and may be first cycle.

Corundum

Corundum has been positively identified in only one sample, Pembina 1-10-A. This was a sample taken from the shale just above the conglomerate. While only a few grains were present, these represented fifty per cent of the non-opaque minerals present. Several other grains that might possibly be corundum have been noted in one or two other samples. It is identified by refractive indices above 1.66, uniaxial figure, low first-order interference colours, slight bluish or pinkish colour and very slight pleochroism. The grains are angular to subangular and so are probably first-cycle.

Diopside

Diopside is not a common mineral, only two or three grains at the most being seen in any one slide. There is too little to see any pattern of distribution between the Foothills and the Pembina area. It is characterized by being colourless to light green, having high interference colours, an extinction angle of about 40° and a prismatic habit. The grains are subangular to subrounded.

Epidote

Epidote has been noted in only one sample, #3413, from the Foothills. It is identified by a yellowish-green colour, slight

pleochroism, high interference colours arranged in concentric rings, refractive indices above 1.66 and almost glassy appearance. The grain is rounded.

Garnet

Garnet is present, in varying amounts, in nearly all the samples studied. It is quite a bit more plentiful in the Pembina samples than in the Foothills samples. At least two types have been identified.

One may be called a normal detrital type. The grains are irregular, colourless, very light blue or slightly yellow, and show conchoidal fracture. Most are fresh, angular to subangular and are probably first-cycle, but some show marked abrasion and are possibly second-cycle. This normal type is present in all the Foothills samples, where it is the only kind of garnet. It is also present in some of the Pembina samples. A few grains show mineral inclusions.

A second type is decidedly different from the first in that it exhibits crystal faces with re-entrant angles and shows no sign of any abrasion (Plate 2, Figs. 7 & 8). This type is restricted to the Pembina field. A few grains of this type are seen in samples from the Rat Creek well but they show slight rounding. No other type was noted from Pembina 1-10. In the heavy mineral mount the grains are colourless but seen through a stereo-microscope they have a pinkish tinge.

An X-ray powder pattern was run on a pure hand-picked sample of the mineral of the second type in order to get positive identification. The initial heavy mineral concentrate obtained from

P.1-10-H was put through a Frantz Isodynamic Separator (electro-magnetic). The bulk of the mineral was concentrated within the relatively narrow range from 0.20 amperes to 0.25 amperes. This is quite a low amperage indicating that the garnet is fairly magnetic. Enough of the garnet was hand-picked, using a biological culture slide and a stereo-microscope, to provide sufficient powder for mounting on the glass spindle of an X-ray machine.

The "d" spacings in Ångström units, were obtained from a powder photograph of the garnet using a 57.3 mm. diameter camera. The photograph was indexed using the following relationship:-

$$\sin^2\theta = \frac{\lambda^2}{4a^2}(h^2 + k^2 + l^2) \qquad (1)$$ (Henry, Lipson and Wooster, 1951, p.177)

Using Henry, Lipson and Wooster (1951), values of "a", the length of the unit cell edge were obtained and are given in Table 3.

Table 3

Data from X-Ray Powder Photograph of Etched Spessartite Garnet

S, mm and θ, degrees	d, Å units	Intensity (10 max.)	$\sin^2\theta$	N (from 1)	(hkl)	$d \times \sqrt{N}$ a_o
15.57	2.872	5	0.0720	16	400	11.49
17.27	2.597	10	0.0881	20	420	11.61
19.77	2.279	<1	0.1144	26	510	11.62
21.22	2.130	1	0.1310	30	521	11.67
24.22	1.880	2	0.1683	38	611	11.59
27.42	1.674	1	0.2121	48	444	11.60
28.52	1.615	2	0.2280	52	640	11.64
29.87	1.548	3	0.2480	56	642	11.58
35.37	1.332	<1	0.3351	76	662	11.61
37.52	1.266	<1	0.3709	84	842	11.61

Average = 11.60

The value for the unit cell edge was used together with the refractive index, 1.80, to determine the composition of the garnet

[illegible]

using a method described by Sriramadas (1957). He correlated the unit cell edge and the refractive index with the composition of garnet, setting up his results as a series of triangular diagrams with garnet compositions as the apices and the two variables superimposed across each diagram. Unfortunately, the values as stated gave three possible compositions:

I		II		III	
Spessartite	81%	Almandite	47%	Almandite	70%
Almandite	14	Pyrope	35	Grossularite	24
Pyrope	5	Andradite	18	Pyrope	6

The "d" spacings as calculated fit those for spessartite much better than they do those for almandite given in the A.S.T.M. Card Index of X-ray data. Also, the unit cell edge and the refractive index are the same as those shown on the spessartite card. It is felt that the first composition is probably the true one, giving the garnet a composition of $81[Mn_3Al_2(SiO_4)_3]$ + $14[Fe_3Al_2(SiO_4)_3]$ + $5[Mg_3Al_2(SiO_4)_3]$.

The extreme angularity of the grains suggests that whatever the process was that produced them, it was authigenic. This process could be crystal growth or etching of detrital grains. Bramlette (1929), in describing similar grains, stated that it was probably not crystal growth, since there was no tendency to develop the typical garnet crystal forms. Bramlette thought etching was the cause. He treated some ordinary crushed garnet with HF and the etching produced was identical with that he had observed on the natural grains. He further substantiated his theory by showing that the lines were purely surface phenomena and not

cleavage. He crushed some etched grains which fractured conchoidally instead of along the lines. The photomicrograph Bramlette shows of the etched grain is very similar to the grains observed in Pembina 1-10. The author feels that the grains under investigation also are a result of etching. The grains are generally smaller than normal detrital garnet grains and also much cleaner, which further substantiates this conclusion. Also, one rounded grain was observed with small, angular etch marks on the surface, identical to the fully etched grains.

As an adjunct to Bramlette's experiment, a garnet crystal showing dodecahedral faces was placed in a 1 N solution of NaOH. After several days, lines parallel to the edges of crystal faces were observed. The angles formed by the edges of the dodecahedral faces and by the etch patterns are 70° and 110°. These are exactly the same as angles measured in the patterns on the grains from Pembina 1-10 (Plate 2, Figs. 7 & 8). Thus, it seems probable that the apparent crystal faces of the Cardium garnet were produced by etching, giving dodecahedral faces.

The exact nature of the etching solution is unknown since both acidic and basic solutions have been shown experimentally to etch garnet. This is further complicated by the normal appearance of the less stable detrital grains, particularly hornblende and apatite. Apatite is more stable in basic solution than in acidic, so it is probable that the etching solution was basic.

A third possible type of garnet is one intermediate between the normal and the extremely etched (Plate 2, Fig. 6). The surfaces of the grains are pitted and irregularly marked, not showing the well-developed crystal faces of the grains in Pembina

1-10. This kind is restricted to samples from Drayton Valley 1-12, which also contain some normal, detrital garnet. The grains are colourless and subrounded to rounded. Whether the surface texture is due to etching or some other cause, such as abrasion, is not known.

If they are etched, the difference between these grains and the extremely etched grains of Pembina 1-10 may be caused by different solutions, different lengths of time for etching or even differences in composition of the original detrital grains.

Hornblende

Hornblende is a relatively rare mineral in the samples. When it is present there are only a few grains. Two types have been noted. One is a bright, slightly yellowish-green colour with slight pleochroism. The other is the darker, blue-green soda hornblende with pronounced dark yellow-green to dark blue-green pleochroism. The latter is quite rare and appears to be confined to the well samples. Hornblende is identified by its colour, prismatic habit, extinction angle of about 16° and indices of refraction near to 1.66. The grains are subangular to subrounded and are most likely first-cycle.

Muscovite

Muscovite is present in nearly all the samples and is quite abundant. It seems to be more abundant in the Foothills' samples and becomes less abundant going east from there. A few grains show perfect pseudo-hexagonal crystal form. Some have inclusions. Most of the grains show some amount of wear.

Rutile

Rutile is one of the more common minerals present. It is found in nearly every sample and occasionally makes up as much as fourteen percent of a sample. More often it is less than five per cent. It appears to be as equally common in the Foothills' samples as in the well samples. However, in two of the wells (Pembina 1-10 and Drayton Valley 1-12) it is more common near the base of the formation. Both the deep red-brown and yellow-brown types of the mineral were noted, with the yellow-brown being more numerous by far. It is identified by its colour, extremely high refractive indices and complete extinction. Several knee-shaped twins were found (Plate 4, Fig. 5). Most of the grains are rounded to well-rounded, but a few are subangular to angular. Probably the angular ones are first-cycle while the others are multi-cycle.

Siderite

Siderite is a mineral with sporadic distribution. In some samples it is so abundant as nearly to obscure the other minerals (up to 47%), while in others it is rare or completely absent. It seems to be somewhat more common in the Foothills samples. It is identified by rhombohedral cleavage, marked change of relief on rotation of the stage, extreme interference colours and n_ω much greater than 1.66. Quite often the grains are coated and opaque with only the distinctive cleavage showing. Many grains, though, are colourless or very light brown. Grains with dust-like inclusions are very numerous. Most grains are worn to some extent, some being subrounded or rounded. The rounding could be caused

by abrasion during transport or by solution. Some grains are subangular to angular and are probably authigenic. It seems likely that all the siderite is authigenic, possibly partly reworked, since clay-ironstone nodules and lenses are frequently found in cores.

Spinel

Spinel is present in less than half the well samples and not at all in the Foothills samples. It nowhere makes up more than five per cent of a sample. There seems to be no distribution pattern in the well samples, except that the Drayton Valley well has little. It is identified by its deep brown-red colour (almost opaque), isotropic character and index of refraction greater than 1.66. The grains are subrounded to angular, show the characteristic conchoidal fracture, and are probably first-cycle and possibly some second-cycle.

Topaz

Topaz has been positively identified in several samples and is suspected in several others. Only one or two grains are present in any slide. It has been found in both the Pembina and Foothills samples. The grains are colourless, non-pleochroic, have a refractive index less than 1.66, are length-slow and biaxial positive. Except for its higher refractive index and biaxial nature, it is very like quartz and it is possible that some topaz is overlooked in mistake for quartz. The grains are subangular and probably first-cycle.

Tourmaline

Tourmaline is one of the two most common minerals and is present in every sample. Several types have been noted. One type is very well rounded, the grains being nearly circular. They are usually strongly coloured (schorlite) and often show strong pleochroism. The colours are some combination of green, brown and black and rarely blue (indicolite). Some rounded overgrowths are present (Plate 5, Fig. 2). This type appears to be just as common in the Foothills samples as in the well samples. In the Pembina and Drayton Valley wells it becomes less abundant toward the base of the formation. The grains are definitely multi-cycle.

A second type includes grains which are rounded to subrounded and subhedral, although some are irregular. The crystal form of these grains is prismatic or tabular. The grains are coloured much as those of the first type but a larger proportion are pleochroic, from colourless or slightly pink to dark brown. Some blue grains were noted. This type is more abundant in the Pembina area than in the Foothills and is also more abundant at the top of the interval sampled than at the bottom. These grains are probably multicycle also.

A third type includes the subangular and angular grains and is subdivided on the basis of euhedral and irregular grains. The grains show little or no wear and are usually strongly pleochroic, going from colourless or pink to dark blue, dark bluish-brown or dark brown. One zoned grain of this type was seen (Plate 3, Fig. 4). This type is not common in the well samples and is not present at all in the Foothills samples. The grains are almost certainly first-cycle.

Volcanic Glass

Volcanic glass has been identified in several samples from the Pembina area and the Foothills. It is identified by its medium to dark brown colour, isotropic character and index of refraction less than 1.66. The grains are angular and fresh and are certainly first-cycle.

Zircon

Zircon is the most abundant heavy mineral present. It shows a marked decrease in abundance in the Foothills samples, unlike tourmaline, and shows a marked increase in abundance with increase of depth in two of the wells, also unlike tourmaline. In Pembina 1-10 and Drayton Valley 1-12, zircon is much more abundant than tourmaline, especially near the base. However, in the Rat Creek well, zircon is about equal in abundance to tourmaline and shows no increase with depth. This is very similar to the Foothills samples, where zircon is about equal to tourmaline.

Like tourmaline, zircon is divided into four types. The first is the very well-rounded, almost circular zircon grain. This type has no original crystal form left. The grains are usually coloured, either dark grey, dark greyish-brown, or purple (hyacinth). No accurate count of the hyacinth-type zircon was made but a rough count was made for some slides. This indicated that the hyacinth zircon makes up, on the average, fifteen per cent of the very well-rounded type or about ten per cent of the zircon population. This type makes up over half of the zircons present and the abundance of very well-rounded zircons increases markedly with depth.

A few of the coloured grains show weak pleochroism, several zoned ones were noted (Plate I, Fig. 8) and many have inclusions. These grains are undoubtedly multi-cycle and the hyacinth variety is considered to be of Precambrian origin.

The second type includes those grains that are rounded to subrounded and subhedral. Prism faces and pyramidal terminations are the forms commonly retained, and some of the grains are elongate, worn rods. These grains are far less numerous than the very well rounded ones, but still occur in every sample. They are more abundant near the top than at the bottom and appear to be slightly more abundant in the Pembina area than in the Foothills. The grains are usually light to medium grey and turbid, but less turbid than the very well rounded kind. Some of the grains have inclusions, a few show zoning, and one or two knee-twins were noted. They are probably multi-cycle.

The third and fourth types are angular to subangular grains, either euhedral or irregular. These grains are relatively rare, although more common than their tourmaline counterparts. They are not present at all in the Foothills samples. They appear to be more numerous in the centre or upper centre part of the interval sampled in the wells. On the whole, the irregular grains are slightly more numerous than the euhedral grains. They are colourless and usually water clear, showing little or no wear. Often, the euhedral grains are elongate and needle-like with well-terminated ends. Many grains have inclusions, usually oriented parallel to the c-axis. The grains of these two types are undoubtedly first-cycle.

Among the grains of the last type, several grains that could possibly be cassiterite were noted. They had much paler interference colours than the rest of the zircons and were quite stubby, unlike most of the euhedral grains. The suspected grains were noted in Pembina 1-10-H.

The interference colours of the last type on the whole were higher than those of the more rounded and presumably older types. Similarly, the turbid appearance, giving the grains a grey colour, increases with increasing roundness and age.

Zoisite

Zoisite (of the orthorhombic system) is a quite rare mineral, although it is possible that some has been mistaken for chloritoid. It is identified by its low first order, sometimes anomalous "Berlin" blue, interference colours, slightly blue-green colour and refractive index above 1.66. The grains are subrounded but may still be first-cycle.

Unidentified

An unidentified mineral has been noted in several of the well samples, mostly those from Pembina 1-10, although it is not in the samples from the Foothills. This mineral is subhedral and subrounded to rounded, usually occurring as worn prismatic or tabular grains as shown in Plate 2, Figs. 9 & 10. It is a brownish-yellow colour and usually is slightly pleochroic, medium brownish-yellow to medium greenish-yellow. No good interference figure was obtained for it. It has parallel extinction and refractive indices above 1.66, about the same as zircon. The interference colours are masked by the colour of the mineral. On some grains

striations cross the prism face at about 60° to the edge, and on one grain two sets were noted, making an angle of about 65° with each other. This mineral fits the description for cassiterite as given by Milner (1952, pp. 258-259) very well, even to the slight greenish pleochroism, but a positive identification was not possible.

Description of Opaque Heavy Minerals

Hematite

Hematite is an uncommon mineral, seen only in the Foothills samples. It is identified by its bright red colour and metallic lustre under incident light.

Ilmenite

Ilmenite is quite a common mineral, being second in abundance to pyrite among the opaques. It may be somewhat more abundant in the Foothills samples than in the well samples. It is characterized by its metallic lustre and black colour under incident light. Some magnetite may be included here, but all the magnetite should have been taken out by the hand-magnet, so it is assumed to be all ilmenite. The grains are usually subrounded to rounded.

Leucoxene

Leucoxene is also a fairly abundant mineral but is more sporadically distributed than ilmenite. Only occasionally is it more common than ilmenite. It is characterized by its white colour under incident light. The grains are usually rounded to subrounded.

Pyrite

Pyrite is the most common opaque mineral. In nearly all of the samples it makes up fifty per cent or more of the opaque minerals and in some it is over seventy per cent. In a few samples, notably Pembina 1-10-A and D, pyrite makes up the bulk of the total heavy minerals. It occurs in aggregates of euhedral cubic crystals, irregular aggregates and, more rarely, as single euhedral cubic crystals and as perfectly circular forms. These latter are like the forms described by Love (1957) as "framboids", which he found were pyritized siliceous micro-organisms. Many quartz grains are among the heavy concentrates because of small pieces, usually crystals, of pyrite attached to them. From this it appears that most, if not all, of the pyrite is not detrital but formed authigenically.

Percentage Distribution of Heavy Minerals

The percentage of heavy minerals in each sample was calculated and tabulated.

The average heavy mineral content of the Foothills is 0.09 per cent, the maximum being 0.28 per cent. In all the sampled sections but one the heavy mineral content increases towards the top of the section. The exception, from the McLeod River, shows a very marked increase in the middle sandstone member.

The samples from the Pembina area show a considerably higher heavy mineral content than those from the Foothills. Those from Pembina 1-10 have an average of 0.35 per cent with a maximum of 1.03 per cent (excluding 6.46 per cent from a siderite cemented sandstone). Those from Drayton Valley 1-12 have an average of 0.30 per cent with a maximum of 0.80 per cent. Those from Rat

Creek B-12 have an average content of 0.26 per cent with a maximum of 0.39 per cent. This shows an increase from west to east in the Pembina field, carrying on the trend from the Foothills.

In Rat Creek B-12, the heavy mineral content increases toward the top of the sampled section. In Drayton Valley 1-12, the content is at a maximum at the centre of the sampled section. No pattern is discernible in Pembina 1-10.

Thin-Section Study

A total of fifty-six thin-sections, forty from the Pembina wells and sixteen from the Foothills outcrops, were examined. All but one of the subsurface thin-sections come from the predominantly sandstone part of the Cardium formation. Pembina 1-10-1-1 comes from the overlying black shale. All the Foothills thin-sections are of sandstone.

Foothills Area

The Foothills thin-section samples come from five fairly widely-spaced outcrop localities in the central Foothills, from the McLeod River in the north to the South Ram River in the south. Their locations are given in Appendix C. The sandstones examined fall into several groups, from lithic wacke to quartz arenite (Williams, Turner and Gilbert, 1955). The majority are quartz or lithic arenites. A few of the quartz arenites would fit into the orthoquartzite group ($>$95 per cent quartz framework), (Pettijohn, 1957, pp. 291 & 316) but most of them and all of the lithic wackes would fit into the protoquartzite group (ibid.)

In size, the sandstones range from very fine to medium

grained sand with occasional grains in the coarse and very coarse sand sizes. Eight are very fine grained, six fine grained and two medium grained. In general, grain size increases from bottom to top of the section and the two coarsest samples come from the top of their respective sections.

There appears to be a relation between size, degree of rounding and sorting (or amount of matrix). All but one of the wackes (the poorest sorted sands) have a grain size of 0.10 mm. or less and these also contain a larger proportion of more angular grains. This is in part explained by the fact that small quartz grains abrade less easily than large ones. Also, a cause, in part, would be that the wackes did not undergo the prolonged winnowing and sorting of the arenites.

The main detrital constituent of the sandstones is quartz. In all but two of the samples it represents more than fifty per cent of the grains, reaching seventy-five per cent in several samples. It is of both igneous and metamorphic origin. Quartz of igneous origin shows sharp extinction, while that of probable metamorphic origin shows undulatory extinction. The abundance of quartz with undulatory extinction varies from twenty per cent to about fifty per cent. The abundance of metamorphic quartz seemingly increases towards the top of the section. While many grains have inclusions, both mineral and dust-like, such grains generally show sharp extinction. The bulk of the grains are subangular to subrounded, relatively few being rounded or angular. However, many of the grains have overgrowths in optical continuity, the original rounded to subrounded grain being outlined by a dust-ring, probably of iron oxide. The number of grains having visible over-

growths varies considerably between samples. Sometimes secondary silica makes up five per cent of the rock, but normally there is one per cent or less.

Chert and microquartzite, quartzite composed of grains smaller than sand size, are the other main framework constituents but are much less abundant than quartz. Together, quartz, chert and microquartzite usually make up more than eighty per cent of the total rock.

Other rock fragments are also present but rarely make up over ten per cent and never more than fifteen per cent of the total. They are largely shale with a varying silt content.

Cement, in the form of secondary silica, carbonate and/or iron oxide, is present in all samples, usually in an amount of about five per cent. Secondary silica, as quartz overgrowths, is present in small amounts in all the samples. Carbonate content, on the other hand, varies from nil in some samples to twenty-five per cent in #3252. Iron oxide is not a common cementing agent, being present in only four samples and there in amounts of less than five per cent. There is more cement in the Foothills samples than in those from the Pembina area.

The matrix is composed of clay minerals with some silt- and clay-sized quartz. It usually makes up less than ten per cent of the rock, but in a few samples it reaches fifteen or twenty per cent. The clay minerals present are probably illite, chlorite and possibly some kaolinite (see pp. 49-51).

Heavy accessory minerals have already been described in detail.

In no slide is there even one per cent of feldspar. Only half-a-dozen or so grains are present in any one slide. The

feldspar noted is twinned plagioclase and microcline and a very few clouded orthoclase grains. Probably some orthoclase has been overlooked as being quartz, but this would be a relatively small amount, not more than one or two per cent. The feldspar varies in condition from fresh and subangular to almost completely kaolinized or sericitized and more rounded. Some detrital calcite appears to be present, particularly in #3252, where the grains are surrounded by an iron oxide ring.

Pembina Area

Several different lithologies were sampled for thin-section examination from the Pembina wells. These are: shale, conglomerate, "clean" sandstone from the oil producing horizons, interbedded silty shale, "dirty" sandstone and "clean" sandstone from the non-producing horizons, and clay ironstone.

The sample of shale came from Pembina 1-10, just above the conglomerate. In thin-section, it is shown to be quite a silty shale, since it contains about twenty-five per cent silt-size quartz. The grains are mostly subangular, with some subrounded. Most have sharp extinction and are quite fresh. The more rounded ones seem to be somewhat corroded. Some detrital silt-size muscovite, biotite and feldspar (Carlsbad twin) is present also. The shale is quite dark, probably from organic material, and there is a minor amount of pyrite. The clay minerals are aligned roughly parallel and give an indication of bedding. The quartz grains are not noticeably aligned.

One sample of conglomerate for thin-sectioning was taken from each of the wells. All three are orthoconglomerates, (Pettijohn,

1957, pp. 256, 261).

The phenoclasts of the conglomerates are mainly chert, quartzite with a little vein quartz and some shale and siltstone rock fragments, some of which are chertified or silicified. All the pebbles are highly rounded. This indicates that it is a mature deposit and places it in the orthoquartzitic or oligomict conglomerate category (Pettijohn, 1957, p. 256). Many of the pebbles have been fractured previously and the fractures filled with chert or chalcedony.

The pebbles in all three slides show sutured and concave contacts (Plate 9, Fig. 2). This is best illustrated in Pembina 1-10-3-2a. Even in Rat Creek B-12-1, which has about forty per cent matrix (material <1 mm. diameter), sutured contacts are common. Many pebbles of Drayton Valley 1-12-5-0 are fractured and the fractures are infilled with calcite cement, which makes up twenty-five to thirty per cent of the rock. In some places the calcite is replacing the chert and quartzite (Plate 9, Fig. 1). It could be that cementation took place almost simultaneously with deposition, because the framework, while intact, is very loose (about one contact per pebble only). Then, at some later time, perhaps due to load, pebbles were fractured and the cement forced into the spaces formed. The cement does show twinning, probably due to pressure. Alternatively, the fracturing took place shortly after, or even during, deposition and the cementation was immediately afterwards. The latter explanation seems less likely. In Drayton Valley 1-12-5-0 there is a small amount of chert or chalcedony cement, which also infills fractured pebbles. It sometimes occurs in small patches beside a pebble, completely surrounded on

the other sides by calcite cement. Thus, it was probably deposited before the calcite cement. It sometimes gives an anomalous biaxial positive interference, indicating stress, and appears recrystallized.

Matrix in the conglomerates is variable in amount, as is cement. In Drayton Valley 1-12-5-0, there is only five per cent matrix (sand and silt size quartz and chert) but thirty per cent cement (twenty-five per cent calcite, five per cent chert). In the other two there is much less cement than matrix, Pembina 1-10-3-2a having one per cent (calcite) and Rat Creek B-12-1 having nil. The sample from Pembina 1-10 has fifteen per cent matrix, while that from Rat Creek has forty per cent. In both it is made up of subangular to rounded sand-size and silt-size quartz (the finer particles being more angular) and clay minerals.

The average size of the pebbles is about four millimetres, but some go up to eight. There is also a certain amount of very coarse sand which is included in the framework. None of the three are particularly well sorted, Pembina 1-10-3-2a being the best and Rat Creek B-12-1 the worst.

The conglomerate, then, is of the mature orthoquartzitic type and it has undergone considerable pressure, probably due to load.

Samples for thin-sectioning were taken from the oil-producing horizons of each of the three wells. All but two are from the upper sandstone unit. These are all, of course, 'clean' sandstones. There is very little difference in any of the slides and all but two are classed as quartz arenites, the others being a lithic arenite and a quartz wacke (Williams, Turner & Gilbert, 1955).

The lithic arenite would fall into Pettijohn's group of protoquartzites, (1957, pp. 291 & 316), which he considers to be a winnowed greywacke. In fact, most of the quartz arenites would fall into this group, since they do not have more than ninety-five per cent of the framework as quartz. The quartz wacke would fall into Pettijohn's lithic greywacke group.

There seems to be some relationship between grain size and sorting, as shown already by the mechanical analyses, and between grain size and angularity, as shown in the Foothills sandstones. There are two samples with average grain size less than 0.10 millimetres and these are markedly more angular and less well sorted than the others.

The main constituent of the sandstones is quartz. It varies in amount from forty-five to seventy-five per cent of the framework, but in most of the samples makes up sixty to seventy per cent. The grains are usually subangular to rounded, with more in the rounded and well-rounded classes than in the Foothills samples. There are fewer grains with overgrowths than in the Foothills samples, and as in the latter, the overgrowths give the originally rounded or well-rounded grains an appearance of angularity. Overgrowths are not very common in the Pembina area samples, usually less than five per cent of the grains having them.

From fifteen to fifty per cent of the grains show undulatory extinction, suggesting that they are of metamorphic origin. The average content would be about twenty-five to thirty per cent. The originally igneous quartz grains have inclusions, usually mineral or dust-like, while the metamorphic quartz grains have few. A few of the grains appear clouded and corroded.

Chert and microquartzite are the other two main constituents of the framework. They are always subordinate to quartz, although occasionally not much so. Chert is nearly always more abundant than microquartzite, with the average chert content being about eleven per cent and that of microquartzite about eight per cent. The quartz-chert-microquartzite content ranges from seventy-three to eighty-seven per cent and seems to influence the sorting. Those samples with a lower quartz-chert-microquartzite content are less well sorted than those with a higher content. This was shown already by the relationship between the percentage of sand-size material and the sorting. Generally, the chert and microquartzite grains are better rounded than the quartz grains. Most of the quartz and all of the chert and microquartzite grains are multi-cycle.

Other rock fragments make up about five per cent of the framework, in one case over ten per cent. The fragments are shale and silty shale. They are not so well rounded as the siliceous grains.

Cement is not a prominent feature of these samples and, except in one case, makes up less than five per cent of the rock. Calcite and secondary silica, in the form of overgrowths, are the cementing minerals. In one or two samples, pyrite is an additional cement, as it appears to be authigenic.

Matrix content is variable, though usually about five per cent. In one sample, Pembina 1-10-4-7, there is fifteen to twenty per cent. It consists of fine silt- and clay-size quartz, and clay minerals. An attempt to determine the clay mineralogy by X-ray methods was made and the results are given in the clay mineralogy section (pp. 49-51).

The accessory heavy minerals have already been described. Feldspar is almost totally lacking, as in the Foothills samples, although there seems to be a slightly higher content in the Pembina area samples. Most of the grains noted were twinned plagioclase and potassium feldspar, although a few untwinned orthoclase grains were seen. Probably a certain amount of orthoclase was mistaken for quartz, but, as in the Foothills samples, it is unlikely that it is very much.

The deposits have evidently undergone a considerable amount of pressure, probably due to load, since many mica flakes are bent and crenulated and there is a large number of long and concave contacts between quartz grains (Taylor, 1950).

The oil bearing sandstones of the Pembina area are mature quartz arenites, well sorted, well indurated, very fine to fine grained with most grains being subrounded. In composition they are very similar to their Foothills counterparts but are slightly different in texture. The quartz arenites from the Pembina area are finer grained, better sorted, and less well cemented, and the grains show, on the average, better rounding than those from the Foothills.

A number of samples were taken from the parts of the three wells that showed complexly interbedded or completely and irregularly intermixed sandstone and shale. In the majority of cases it was found not to be sandstone and shale but "clean" sandstone and "muddy" sandstone or sandy shale.

The "clean" sandstone is exactly like that of the oil-producing horizons described above and, indeed, in hand specimens shows oil-staining. The "muddy" sandstone is much the same except that it has from forty to eighty per cent matrix. Occasionally, there

is some true shale with ten to twenty per cent sand- and silt-size quartz.

In many cases there is a sharp contact between the "clean" sandstone and the "muddy" sandstone or shale, often with a thin pyrite layer. In other cases there is a gradational contact or virtually no contact.

Nearly always the "muddy" sandstone has a reworked appearance. Worm burrows or those of similar organisms have been seen in the core (Plate 8, Fig. 5), and the reworking has probably been done by them. Shepard and Moore (1955) state that burrowing organisms can completely destroy bedding and this is probably the cause of the irregularly mixed "clean" sand and "muddy" sand in some samples.

Clay ironstone or sideritic mudstone nodules and lenses were noted while the cores were being examined and thin-sections of several of these obtained. The thin-section was made so that the contact between the ironstone nodule and the normal clastic sediment was preserved.

In all cases the contact is definite but in some it is to some degree gradational while in others, Pembina 1-10-3-2b, it is exceptionally sharp and probably represents a slight depositional hiatus. Two of the contacts are marked by pyritiferous zones, one several millimetres thick.

The clay ironstone or sideritic mudstone is composed of varying quantities of microcrystalline siderite, clay mineral and sand- and silt-size quartz and chert. The colour of the ironstone is from medium to dark brown. It is more homogeneous than the clastic sediments and appears denser. Between crossed nicols it

gives the characteristic high birefringence of siderite. In one case, there is about ninety to ninety-five per cent siderite with some clay mineral, the remainder being mostly sand-size quartz. The quartz is the same as that in the underlying sandstone, except it is more angular. In three samples there is from sixty to eighty per cent siderite, which occurs together with a considerable amount of clay mineral. There is only about thirty per cent siderite in another sample (Pembina 1-10-6) where it acts more as a cement for the quartz and chert grains.

Representative thin-sections of all types are described in detail in Appendix B.

Clay Mineralogy

Procedure

Samples from Pembina 1-10 and the Foothills (Appendix C) were prepared for X-ray analysis. This was done by allowing the clay-sized material to settle out onto glass slides, producing basally oriented clay samples.

The slides were X-rayed, both dry and glycolated, using Cu radiation, a Norelco diffraction unit and wide-angle goniometer. The resultant graphs were analysed and the "d" spacings (in Ångströms) calculated.

Results

Only the graphs of the dry mounts are compared in detail, since the glycolated mounts were run only to detect the presence of montmorillonite. The graphs of the glycolated mounts are very similar to those of the dry, showing no increase in basal spacings.

This fairly certainly rules out the presence of montmorillonite in these samples. However, in taking photographs of a cut surface of sample Pembina 1-10-C (Appendix C) water was put on it. After the water had dried, a considerable swelling of some of the shale laminae was noticed, indicating the presence of montmorillonite or vermiculite.

The graphs of the dry mounts are strikingly similar, with one or two exceptions. All have the largest peaks at 4.23 Å and 3.33 Å, the latter always being the larger. The 4.23 Å spacing corresponds to a quartz spacing (4.26 Å), indicating the presence of silt- and clay-size quartz. The 3.33 Å spacing is a strong quartz reflection but is also the 3rd order of the basal reflection for muscovite and illite. A peak occurs about 9.9 Å in all the samples, which is the basal spacing of muscovite and illite. There are also several other peaks on the graphs which correspond to muscovite and illite spacings. Muscovite can be seen megascopically and microscopically in all the samples, so it is probable that it is also present in clay-sized particles. It has been shown that illite may be composed of clay-size muscovite, a mixed-layer muscovite-montmorillonite, or a mechanical admixture of muscovite and montmorillonite (Mason, 1958, p. 153). Essentially, then, it is a rather general term for clay-size mica.

All the samples produce peaks at about 7.00 Å (up to 7.08 Å), indicating the probable presence of chlorite or kaolinite. Since the peaks are quite small, there is probably not much more than the minimum required to show on the graph (about five per cent).

A very strong peak is produced at 7.50 Å on the graph from the outcrop shale sample (T.S. Big. 173' - 183'). This peak, or

one very close to it, occurs as a small peak in three of the four well samples but not at all in the outcrop sandstone sample. The spacing is very close to the strongest spacing for gypsum (7.56 Å) and does not correspond to any for the common clay minerals. Nor does it correspond to any strong spacing for the common accessory minerals such as quartz and calcite.

The graphs of the outcrop sandstone and of the outcrop shale are fairly similar, except for the peak at 7.50 Å already mentioned.

On the whole, there is no difference in clay mineralogy in any of the samples. The minerals present are illite (probably clay-size muscovite), probably chlorite and clay-size quartz. Gypsum is present in four samples.

CHAPTER V

GEOLOGICAL HISTORY

Provenance

The bulk of the material making up the coarser clastic phase of the Cardium formation came from the erosion and subsequent deposition of pre-existing sediments, located somewhere to the west of the present Foothills belt. This is shown by the predominance of multi-cycle rounded chert, quartz and microquartzite grains. Also, it is indicated by the abundance of the rounded stable heavy mineral assemblage, predominantly zircon and tourmaline, amongst the heavy accessory minerals.

The region in the vicinity of the present day Selkirk Mountains has been considered the source area for the sediments of the Cardium formation by some authors (Beveridge, 1956; Patterson and Arneson, 1957; Gallup, 1957). Thickening and coarsening of the beds from east to west and brackish water conditions that existed in upper Cardium time in the Foothills indicate a western source for the sediments. They probably came mainly from earlier Mesozoic, and possibly Paleozoic, sedimentary rocks deposited in the region of the present Rocky Mountains and not from rocks in the region of the present Selkirks.

However, the metasedimentary rocks of the Belt series in the area of the Selkirks did contribute some of the sediment. This is shown by the presence of such metamorphic mineral species as: chloritoid, spinel, garnet and diopside. Since they form a small portion of the heavy mineral suite, it is probable that the clastic material from this area was a relatively small part of the total supplied to the central Foothills area. There was also some small

contribution from an acid igneous source in the same area, as shown by the presence of first-cycle apatite, zircon and tourmaline.

A significant point is the almost complete absence of feldspar. In this, the Cardium formation is, together with the Viking formation, (Young, 1959) quite unusual. The Blairmore formation of Lower Cretaceous age has a considerable feldspar content in its upper part which is interpreted as indicating an igneous source (Glaister, 1958). The Upper Cretaceous clastic strata above the Cardium formation are feldspathic, indicating an igneous source in the Selkirks (Warren, 1951). However, according to Warren (1951), the upper Edmonton formation has no feldspar and he takes this as showing that the area of the present Rocky Mountains was uplifted and cut off the farther west source of feldspar.

Using this analogy, it seems likely that the uplift which caused the retreat of the sea was relatively minor in the Rocky Mountain area. This, then, would be a preliminary to the major orogeny that took place at the end of Cretaceous time. The land was quickly raised, as shown by the relatively swift change from shale to sandstone. The diastrophism probably affected the area west of the present trench, which at this time was probably quite low-lying, to a very minor degree. Streams flowing eastward from this area had to cut through the uplifted area in the present Rocky Mountain area, in a way similar to the present day Peace and Liard Rivers. In doing this they would pick up the bulk of their detrital material from the Mesozoic and, possibly, Paleozoic formations exposed. Since the area west of the present Rocky Mountain Trench was relatively flat, most feldspar contributed by

it would be eliminated during weathering and transportation. Similarly, only the more stable metamorphic minerals would survive.

There is some difference in the heavy mineral suites of the Pembina area and the Foothills. This is very slight and is as much in amount of heavy minerals as it is in number of species. As has been shown before, the Foothills samples contain a smaller amount of heavy minerals than the Pembina samples. The Pembina samples also show some increase in heavy mineral content to the east, in a matter of some twenty miles. In addition to this, spinel is entirely absent in the Foothills samples while chloritoid, hornblende, diopside, zircon and garnet are quite a bit less abundant in the Foothills than in the Pembina area. There are several possible hypotheses which could account for this. One is that the Pembina area had an additional source of sediment, very similar to that which supplied the Foothills but supplying a few different heavy minerals. This additional source could be uplifted pre-existing sediments to the northwest of the Pembina area, probably somewhere in the Peace River area. The Cardium formation becomes thicker to the northwest, strengthening this hypothesis. The Pembina area is only several hundred miles south of the Peace River area and alongshore currents moving south could distribute a considerable amount of material.

A further explanation could be that the heavy minerals were concentrated in the Pembina area by the same processes that concentrated the quartz sand. This would apply especially to the zircon, which is relatively more concentrated in finer grained sandstones (Van Andel, 1959). The sandstones of the Pembina area are finer than those of the Foothills.

A third possible cause could be intrastratal solution. This is very likely since the mineral species present in the Pembina samples and absent in the Foothills samples are the chemically unstable ones (hornblende, spinel, diopside and garnet). The same solutions that precipitated the silica cement in the Foothills samples could have removed, to a great extent, the unstable minerals. Since there was little or no silica cementation in the Pembina area, intrastratal solutions may have been less active there. This would also explain the slight differences in heavy mineral content seen over the Pembina area. Samples from Pembina 1-10 contain a greater variety and more heavy minerals than the others. This could be because that part of the area was less permeable than the others. There were sufficient solutions to etch the garnet of that part but in the other parts there may have been more solution activity which completely removed the etched garnet.

The presence of euhedral zircon, volcanic glass and probably montmorillonite in some shale laminae, indicates that there was some volcanism during Cardium time.

The source of the shale and the conglomerate above the sandstone is slightly different than that of the sandstone, since the shale contains corundum. The sandstones do not contain corundum. This also indicates that the shale and conglomerate belong to a different sedimentational unit. The source of the chert pebbles in the conglomerate, which are obviously multicycle, was probably the uplifted Cadomin conglomerate.

Depositional Environment

The depositional environment during pre-Cardium Blackstone

time was apparently quiet, fairly deep water with a very small coarse clastic contribution.

However, uplift during Cardium time brought an end to these conditions. The sea receded toward the east and the bulk of the Cardium formation in the Pembina and the Foothills area was deposited in relatively shallow, agitated water. Sea-level was not constant but fluctuated fairly often, as is shown by large and small scale interbedding of sandstone and shale.

The Cardium formation in the Foothills has always been considered a nearshore type of deposit (beach or deltaic, Mountjoy, 1957), especially since the upper sandstone member contains local coal, showing brackish water (lagoonal?) conditions.

The depositional environment of the Cardium formation in the Pembina area is not entirely agreed upon. Beach (1955) felt that the Cardium formation was a turbidity current deposit, the evidence being mainly the presence of the conglomerate unit above the upper sandstone. This study has shown that the conglomerate does not belong to the same sedimentation unit as the sandstone. Thus, their depositional environments cannot be compared.

The writer is of the opinion that the Cardium sandstone shows none of the features commonly attributed to turbidity current deposits, except the complex interbedding of shale, muddy sandstone and clean sandstone. The latter can be explained by small-scale penecontemporaneous slumping under normal shallow-water conditions. The clean sandstone is excellently sorted, nearly the maximum, which would not be expected if it were a turbidity current deposit, as the mechanism requires a considerable clay content. A sorting coefficient between 1 and 2 (averaging about 1.45) is indicative

of deposition in a near-shore marine environment (Stetson and Upson, 1957, p. 57). There is no east-west variation in grain size across the Pembina area, nor any vertical variation. The vertical uniformity in grain size shown by the mechanical analyses is all the more remarkable when it is considered that the sampled intervals were not continuous sandstone beds but alternating sandstone and shale. Depositional conditions must have been strikingly similar not only over a considerable area but over a considerable period of time, at recurrent intervals.

The clean sandstones compare very favourably in almost all respects to the deposits of the "nearshore gulf" environment as defined by Shepard and Moore (1955). To show this, the results of the mechanical analyses were plotted on the sand-silt-clay triangular diagram devised by Shepard and Moore to distinguish environments. This is given as Fig. 5. It compares very closely to their diagram for the nearshore gulf environment and does not fit any other environment as well. Another feature they found was that the nearshore gulf deposits had a greater amount, on the average, of very fine sand (1/8 - 1/16 mm.) than any other type of environment in the Gulf of Mexico. The overall sand content averaged about ninety-one per cent, decreasing toward the base of the slope (p. 1537), while the very fine sand content ranged from about fifty per cent to over ninety per cent with the average over eighty per cent (p. 1537). This compares extremely well with the sandstone samples from the oil-producing horizons used for mechanical analysis.

These clean sands are also similar to the deposits of the unda environment and to the undaform-edge sands as defined by Rich (1951). The undaform is above wave-base and is part of the

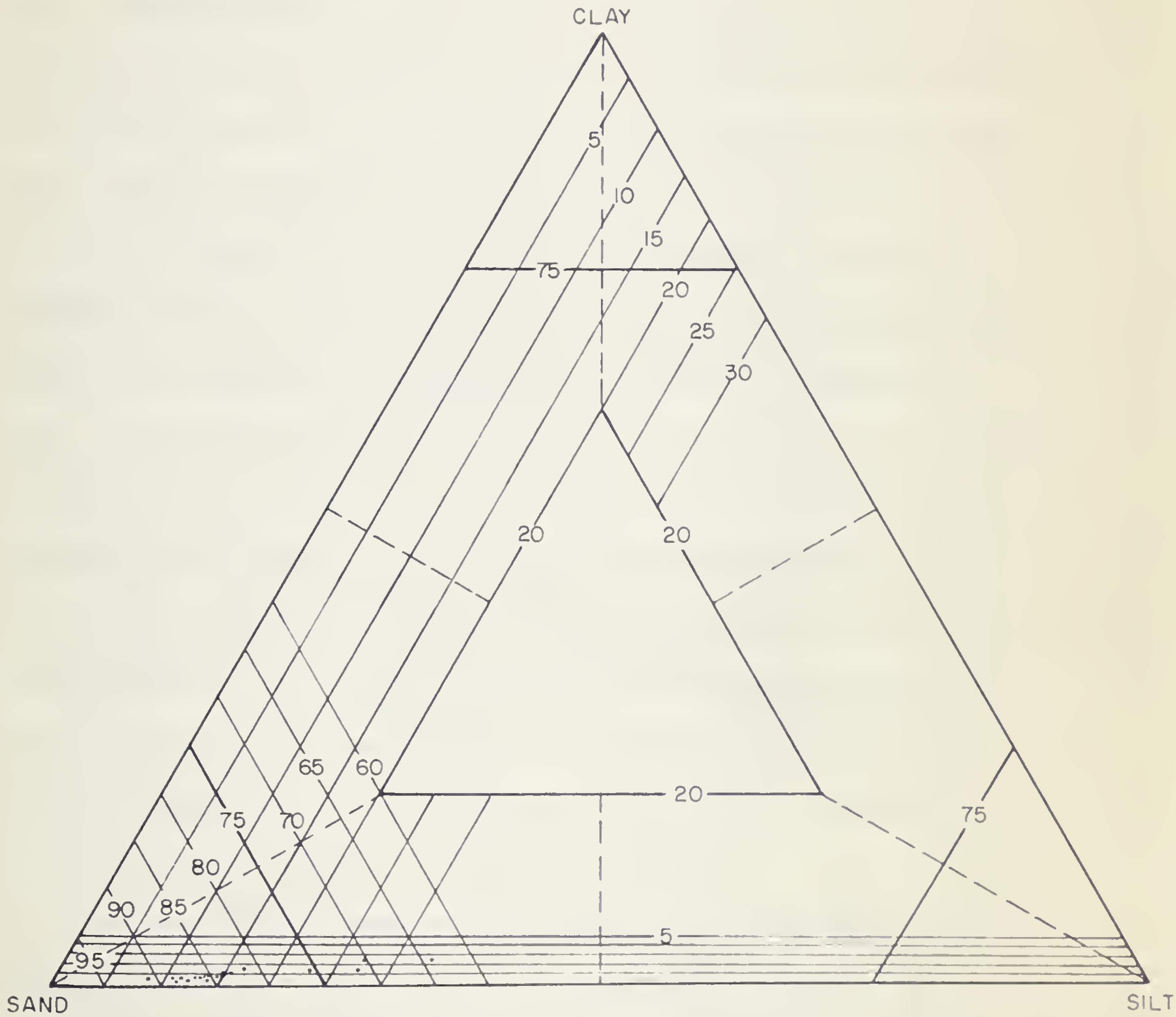


Fig 5 Sand-Silt-Clay percentage plotted on Sand-Silt-Clay Diagram
(modified after Shepard and Moore, 1955, — fig no 14)

LEGEND

• Composition From Mechanical Analysis

continental shelf. Its deposits are continuously agitated and winnowed by wave action, which removes much of the finer material. This would leave a well-sorted, mature, fairly well rounded deposit, as are the clean sandstones. Stelck (1955) gives this explanation for the existence of the clean Cardium sandstones in the Pembina area.

The Pembina area in Cardium time was probably close to, or at, the seaward edge of a broad and shallow continental shelf which stretched westward and landward from there some eighty or more miles. Whether the clean sands were deposited there as undaform-edge sands (Rich, 1951, pp. 14-15) or as near-shore gulf deposits on the seaward edge of some barrier islands (Shepard and Moore, 1955) is not certainly known. However, the area was relatively shallow and this shallowness was related to the Paleozoic topography (Roessingh, 1957). The clean sands were the result of a critical sea-level which gave subaqueous winnowing. A slight rise or even fall in sea-level would put the mechanism out of balance. That sea-level oscillated fairly continuously, and was only at this critical level fleetingly and infrequently, is shown by the much larger volume of muddy sandstones and sandy and silty shales. The nature of these latter deposits suggests they were deposited during rises in sea-level above the critical level.

Sea-bottom topography was probably important in determining local thicknesses of clean sand. Shallow areas would be less affected by a rise in sea-level than the surrounding deeper areas, which would then be below wave-base. So, with a rise in sea-level, shallow areas would continue to receive clean sand deposition while deeper areas would get muddy sands and sandy shale. A fall in sea-level would tend to even out the sand distribution,

through erosion.

Certainly bottom topography influenced the deposition of the conglomerate. Its variable and extremely erratic distribution shows this. Where it is thick, it filled in a basin area; where it is thin or non-existent, there existed a shallow area. The conglomerate was a prelude of an advancing sea and with it a return to deeper water conditions.

The conglomerate appears to be a basal conglomerate of an advancing sea and is related to the overlying black shale. In some places, at least, it rests upon a slightly undulating (eroded?) surface of sandstone. There is probably a slight depositional hiatus or diastem represented by the surface between the sandstone and the conglomerate. Krumbein (1942, p. 60) lists a basal conglomerate and a basal black shale (which is sometimes present also, but very thin) as criteria for an unconformity, probably of subaerial origin. In this case it is very slight. It is, as Stelck (1955) suggests, probably the southward extension of the major erosional unconformity underlying the Baytree conglomerate in the Cardium formation of the Peace River area.

At times, during the sandstone deposition, there was quieter, but not necessarily deeper, water over parts of the Pembina area with conditions favourable for the formation of siderite. In some cases, the supply of coarse clastics virtually ceased (as in Pembina 1-10-3-2b) and for a time the "starved basin" environment prevailed. In other cases, there was little or no change in coarse clastic supply but bottom conditions changed. Siderite will form in a very slightly reducing environment at a pH of seven to eight (Krumbein and Garrels, 1952).

Pyrite is fairly abundant, especially in the muddy sands and shales. At times, the anaerobic, reducing environment that is necessary for pyrite formation may have existed at the depositional interface, but most of the time these conditions likely prevailed some little distance below the mud-water interface. In modern sediments, pyrite reaches a maximum concentration some six to eight feet below this interface (Emery and Rittenberg, 1952). Pyrite forms in neutral to slightly alkaline solutions in a more reducing environment than siderite.

Krumbein (1942) lists pyritiferous zones as a criterion for detecting an unconformity. Such an unconformity would probably be of submarine origin. Thin pyrite zones were noted at several contacts between different lithologies, indicating perhaps a slight depositional hiatus.

The depositional environment of the sandstones of the Cardium formation in the Pembina area had a profound influence on their potential as gas and oil reservoirs. The sand was deposited under marine, shallow-water conditions, subject to wave action at a critical sea-level which subsequently winnowed out the fine silt and clay, leaving a well-sorted, potential reservoir sand. Bottom topography determined to a large extent the local thickness of this reservoir sand.

This picture of shallow-water conditions during Cardium time agrees with the ideas of Krumbein and Nagel (1953), Speiker (1949) and Young (1955) concerning the Upper Cretaceous sandstones of the central and north-western United States. It is unlikely that conditions would vary greatly in such a relatively short distance.

Diagenesis and Lithification

In the sandstones of the Pembina area there was minor calcite and silica (in the form of overgrowths) cementation. It was the minor amount of this cementation that enabled the clean sandstones to retain their excellent porosity and become potential reservoir sands. In the Foothills there was much more cementation, especially by silica, which destroyed the original porosity.

The conglomerate in the Pembina area is variably cemented. Some areas have a clay matrix and no porosity while others were winnowed and had considerable original porosity. These porous areas are erratically cemented, mainly by calcite but also by silica. The cementation is such that in a vertical section, one portion may be cemented while the surrounding portions will be porous. The porous parts of the conglomerate act as oil reservoirs. Cementation evidently took place very early, as the cemented conglomerate shows very loose packing. This might also account for the patchiness of the cementation. In the Pembina area there was a certain amount of intrastratal solution, which was responsible for etching the garnet. These solutions also may have eliminated some unstable heavy minerals, especially from the Foothills. It is a possibility that cementation was once more extensive and that the solutions dissolved out most of it.

The fractured pebbles and sutured contacts in the conglomerate, the long and concave contacts between grains in the sandstone and bent and crumpled mica flakes, indicate that the deposits underwent considerable pressure, probably due to load, after deposition. They are five thousand feet below the earth's surface now, and at one time may have had an additional one or two thousand feet of

sediment overlying them. Also, of course, the Pembina area was involved in the Rocky Mountain uplift, though to a small degree, which may have contributed to the pressure.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The dominantly sandstone part of the Cardium formation of the Pembina area acts as an oil reservoir. It correlates, as far as is known, with the lower part of the Cardium formation in the central Foothills. The conglomerate immediately overlying the sandstone at Pembina is homotaxial with the Baytree conglomerate of the Peace River area. The conglomerate marking the "Cardium Zone Top" is correlative in time with the Baytree conglomerate.

Eighteen well samples chosen for mechanical analysis are all very well sorted sandstones with coefficients of sorting ranging from 1.14 to 1.45, the average being about 1.24. The median diameter was about 0.100 millimetres.

A statistical count of the heavy accessory minerals showed eighteen mineral species to be present. Of special interest is the discovery of some strongly etched garnet grains. The grains were etched along crystallographic boundaries. Etched garnet, spinel, and fresh, irregular zircon are absent in the Foothills samples but present in most samples in the Pembina area.

Thin-section study showed that, in general, the well-sorted sandstones of the Pembina area are finer grained, better sorted, better rounded and less well cemented than their Foothills counterparts.

The clay minerals present are illite, kaolinite and possibly chlorite. There is also some clay-size quartz.

The major source for the clastic material of the Cardium formation was most likely Mesozoic and Paleozoic rocks in the area

of the present Rocky Mountains, uplifted by a precursor of the Rocky Mountain uplift which occurred at the end of Cretaceous time. Minor sources were igneous and metasedimentary rocks in the area of the present Selkirk mountains, volcanism during Cardium time and, in the case of the Pembina area, possibly uplifted pre-existing sediments in the Peace River area.

As indicated by this study, the depositional environment of the Cardium formation in the Pembina area was shallow-water, wholly marine conditions, subject to wave action, at least part of the time. The Pembina area, probably at the seaward edge of a broad continental shelf, was somewhat elevated above the surrounding area due to an old Paleozoic high. This enabled the area to be above wave base part of the time, producing the very fine grained, mature, well-sorted, quartz sandstone that acts as the reservoir rock. It is this environment that appears to concentrate the very fine grained sand, which is found to have the best porosity of any sand size.

After deposition, there was circulation of intrastratal solutions, producing the etched garnet. However, this was probably not so great as in the Foothills area, where deposits from solutions tightly cemented the sandstone and probably removed many of the unstable heavy minerals. The conglomerate immediately above the main sandstone in the Pembina area was cemented with carbonate very soon after deposition. Subsequently the pebbles were fractured and the fractures infilled with cement. Subsequent diastrophism during the Rocky Mountain Revolution caused a reversal of the original dip.

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APPENDIX A

Core Descriptions

Core:	Pembina 1-10
Location:	10-1-48-8 W5
K.B. Elevation:	2864 feet
Interval Examined:	5011-5077 feet below K.B. elevation
5011' - 5015.5'	shale - black, silty, non-fissile; 4-inch conglomerate bed at 5014.5', pebbles mainly chert, less than 1 inch in diameter, mudstone matrix.
5015.5' - 5020'	conglomerate - pebbles, varicolored, well rounded, mainly quartz and chert, maximum diameter 1½ inches, average diameter 3/8 inch; upper contact gradational downward from shale to shale with a few pebbles and finally to a true conglomerate; matrix shale, fairly hard, brown in places, possibly sideritic, becomes sandy downward; lower contact missing.
5020' - 5020.5'	shale - black with thin lenses of brown material as in matrix of conglomerate.
5020.5' - 5025.5'	sandstone - brown, very fine to fine grained, cross-laminated, micaceous, oil stained; occasional shale laminae; 4-inch unit of inter-laminated sandstone and shale at 5021.5' showing interlensing.
5025.5' - 5032.5'	sandstone and shale - very thinly bedded to laminated, complexly interlensed; sandstone (60%), brown, fine grained, very thinly bedded and cross-bedded; shale (40%), black, very thinly bedded to laminated.
5032.5' - 5034'	sandstone - brown, very fine grained, hard and dense, possibly sideritic; numerous thin shale lenses.
5034' - 5044.5'	sandstone (90-95%) - brown, fine to medium grained, micaceous, oil stained; thin shale lenses, occasionally up to 1 inch.
5044.5' - 5064'	sandstone and shale - very thinly bedded to laminated, very complexly interlensed; sandstone (50%), brown, fine grained, very thinly bedded, oil stained; shale, black.
5065' - 5065.5'	sandstone (90%) - brown, fine grained, micaceous, oil stained; a few shale laminae.

5065.5' - 5065.75'	mudstone - hard, dense, similar to matrix of conglomerate, possibly sideritic.
5065.75' - 5077'	shale (65%) and sandstone (35%) - very thinly bedded to laminated, complexly interlensed; occasional sandstone lenses greater than 2 inches thick, 4-inch bed at 5066.6' possibly sideritic.

Core:	Drayton Valley 1-12
Location:	12-1-49-7 W5
K.B. Elevation:	2660 feet
Interval Examined:	4488-4548 feet below K.B. elevation.
4488' - 4492'	missing
4492' - 4505'	shale - black, micaceous, occasional sandstone lenses up to ½-inch thick, oil stained.
4505' - 4505.5'	conglomerate - pebbles chert and quartz, varicolored, well rounded, up to 1½ inches long; first appears as a few pebbles set in mudstone matrix which becomes more sandy downwards; concentration of pebbles increases towards base.
4505.5' - 4510'	conglomerate - pebbles varicolored chert and quartz as above, average size 1/8 - 1/4-inch, decreases downwards, calcareous in part; matrix coarse sand; most of last 3' porous, oil stained; lower contact missing.
4510' - 4515'	shale and sandstone - very thinly bedded to laminated, slump structures; sandstone (35%), fine to medium grained, micaceous, oil stained, in lenses up to 2-inches thick.
4515' - 4517'	sandstone (85%) - brown, fine to medium grained, micaceous, oil stained; occasional shale laminae up to 1/4-inch thick.
4517' - 4520'	sandstone and shale - very thinly bedded to laminated, complexly interlensed; sandstone (50%), brown, fine grained, oil stained.
4520' - 4522.5'	sandstone (75%) - brown, fine to medium grained, micaceous, oil stained; frequent shale laminae, occasional thicker units, up to ½-inch thick.
4522.5' - 4523'	mudstone - medium brown, hard, dense, micaceous, possibly sideritic (reacts with 10% HCl).
4523' - 4552'	sandstone and shale - thin bedded to laminated, complexly interlensed; sandstone (50%), brown, fine grained, micaceous, oil stained, in units up to 3-inches thick.

Core:	Stanolind-H.B. Rat Creek B-12
Location:	16-33-48-10 W5
K.B. Elevation:	3199 feet
Interval Examined:	5761-5811 feet, below K.B. elevation.

5761' - 5763.75'	shale - dark grey to black, silty, micaceous, non-fissile.
5763.75' - 5765.25'	conglomerate - pebbles varicolored chert and quartz, up to 1-inch in diameter, averaging about 1/8-inch; matrix shale as above, little or no porosity; upper contact gradational, shale to pebbly shale.
5765.25' - 5766.6'	conglomerate - as above, but matrix mainly sideritic? mudstone with a few black shale lenses, fewer pebbles, no porosity; lower contact very sharp, conglomerate rests on scoured or eroded surface of sandstone.
5766.6' - 5771.3'	sandstone - light brown, very fine to fine grained, thick bedded, micaceous, slightly oil stained; occasional shale laminae.
5771.3' - 5773.5'	sandstone and shale - very thinly bedded to laminated, some complex interlensing; sandstone (80%), light brown, fine grained, slightly oil stained; shale (20%), dark grey.
5773.5' - 5775.5'	sandstone - light brown, fine grained, slightly oil stained.
5775.5' - 5776'	sandstone and shale - as above.
5776' - 5777'	sandstone - as above.
5777' - 5777.5'	sandstone and shale - as above but sandstone (75%) cross-laminated.
5777.5' - 5777.8'	sandstone and shale - very thinly bedded to laminated, complexly interlensed, some mudstone pebbles; sandstone (60%), light brown, fine grained, slightly oil stained.
5777.8' - 5791'	sandstone and shale - thinly bedded to laminated, some complex interlensing; sandstone (75%), light brown, fine grained, cross-laminated, slightly oil stained, units up to 1 foot thick; some shale laminae, thin shale pebble bed at 5780.5 feet.
5791' - 5792'	mudstone - dark brown, dense, hard, siderite (?) 60%, sandstone 20%, shale 20%.

5792' - 5793'	sandstone and shale - complex interlensing; sandstone (75%), light brown, fine grained, cross-laminated, slightly oil stained; some shale laminae.
5793' - 5794.5'	sandstone - light brown, fine grained, thin bedded, slightly oil stained; occasional shale laminae.
5794.5' - 5802'	sandstone and shale - complexly interlensed; sandstone (50%), light brown, fine grained, cross-laminated, occasional unit up to 6 inches thick, concentration of sand decreases downwards.
5802' - 5811'	shale and sandstone - no semblance of bedding, extremely complex interlensing; sandstone (20%).

APPENDIX B

Descriptions of Selected Thin-Sections

Sample Number - 3413

Location - Outcrop at South Ram River Falls, one-half mile below Forestry Road Bridge - second sandstone member, about 50 feet above base.

Description

Colour - fresh surface - light grey
- weathered surface - medium yellow-grey.

Structure - vague indications of bedding.

Texture - clastic, fine-grained sand size (average 0.20 mm.), subrounded to rounded, well sorted, well indurated, well cemented, no porosity.

Main Constituents

75% Quartz - grains subrounded to rounded, average size 0.20 mm. but go up to 0.40 mm., about twenty per cent strained, overgrowths quite common with grain usually rounded to well-rounded beneath, few grains with inclusions (usually mineral), long and concave contacts common.

13% Chert and microquartzite

5% Rock fragments - argillaceous, subrounded.

Accessory Minerals

$<$ 1% Feldspar, Tourmaline, Magnetite, Limonite, Zircon, Chlorite, Hematite, Muscovite

3% Matrix - clay minerals.

3% Cement - SiO_2 overgrowths.

Classification - Quartz arenite.

Sample Number - 3254

Location - South bank McLeod River, about one-half mile west of second bridge, west of Mercoal, Alta. - upper sandstone member - twenty feet below top.

Description

Colour - fresh surface - medium grey
weathered surface - dark grey

Structure - laminated.

Texture - clastic, silt to fine sand size, average 0.05 mm., angular to subangular, poorly sorted, well indurated, no porosity.

Main Constituents

45% Quartz - grains subangular, average size 0.05 mm. but go up to 0.20 mm., about fifty per cent strained, overgrowths rare, some grains have inclusions (iron oxide dust? and mineral), some long and concave contacts.

28% Chert and microquartzite - somewhat better rounded than quartz.

10% Rock fragments - argillaceous, subangular.

Variety Minerals

1% Muscovite - bent.

Accessory Minerals

$<$ 1% Biotite, Hematite, Zircon, Feldspar, Carbonaceous matter, Magnetite, Limonite, Tourmaline, Chlorite

15%$\pm$ Matrix - clay minerals.

Trace Cement - SiO_2 overgrowths and calcite.

Classification - Lithic wacke.

Sample Number - Drayton Valley 1-12-5-0

Location - Well Drayton Valley 1-12, 12-1-49-7-W5
4508 feet below K.B. elevation.

Description

Colour - mottled, medium grey

Structure - nil.

Texture - clastic, fine pebble size, average size 4 mm., well-rounded, fairly well sorted, well cemented, well indurated.

Main Constituents (>1.0 mm.)

35% Chert

5% Vein Quartz - all well rounded.

15% Quartzite and microquartzite

5% Siltstone - dark, well-rounded.

5% Argillaceous material - very dark, silicified, well-rounded. Many pebbles are fractured but otherwise little disturbed and the fractures are infilled with cement which is, in part, replacing the material of the phenoclasts - many pebbles show sutured contacts.

5% Matrix (<1.0 mm.) - quartz and chert, subangular to subrounded.

Cement

25% Calcite - in large crystal-like plates, may be recrystallized, shows pressure twinning.

5% Quartz - earlier than calcite - local - occasionally gives anomalous biaxial positive interference figure.

Classification - Quartzitic pebble orthoconglomerate.

Sample Number - Pembina 1-10-3-3

Location - Well Pembina 1-10, 10-1-48-8-W5
5020.5 feet below K.B. elevation.

Description

Colour - medium brown-grey, oil stained.

Structure - none apparent.

Texture - clastic, very fine to fine-grained sand, average size 0.10 mm., subangular to rounded, well sorted, well indurated.

Main Constituents

75% Quartz - grains mostly subrounded, average size 0.10 mm., thirty to forty per cent strained, about twenty per cent have overgrowths on subrounded to rounded grains, some grains have regular and needle-like mineral inclusions, numerous long and concave contacts.

9% Chert and microquartzite

3% Rock fragments - mainly shale.

Varietal Minerals

1% Muscovite - bent flakes.

Accessory Minerals

$<$ 1% Feldspar, Magnetite, Zircon, Biotite - altered, Garnet, Pyrite.

2% Matrix - Clay minerals

Cement

6% Calcite - patchy.

1% SiO_2 - overgrowths.

Classification - Quartz arenite.

Sample Number - Drayton Valley 1-12-7-2

Location - Well Drayton Valley 1-12, 12-1-49-7-W5
4515.5 feet below K.B. elevation.

Description

Colour - very dark brown, oil stained.

Structure - some bedding.

Texture - clastic, very fine to fine-grained, average size 0.10 mm., subangular to rounded, well sorted, well indurated, some porosity.

Main Constituents

65% Quartz - bulk of grains subrounded, average size 0.10 mm., thirty to forty per cent strained, few overgrowths, some grains with mineral inclusions, many long and concave contacts.

15% Chert and microquartzite

8% Rock fragments - argillaceous material, dark brown.

Varietal Minerals

1% Muscovite and biotite - bent

Accessory Minerals

$<$ 1% Feldspar, Zircon, Garnet, Magnetite, Pyrite, Tourmaline, Leucoxene

5% Matrix - clay minerals

Trace Cement - SiO_2 overgrowths.

5% Pore space

Classification - Quartz arenite.

Sample Number - St. H.B. Rat Cr. B-12-4

Location - Well Stanolind Hudson's Bay Rat Creek B-12, 16-33-48-10-W5
5774.5 feet below K.B. elevation.

Description

Colour - light brown-grey, slightly oil stained.

Structure - none apparent.

Texture - clastic, fine-grained sand, average size 0.1 mm., subangular to rounded, well sorted, well indurated.

Main Constituents

70% Quartz - most grains rounded or subrounded, very few angular, average size 0.10 mm., about thirty per cent strained, very few overgrowths, some grains show mineral inclusions - nearly all grains show long or concave contacts.

17% Chert and microquartzite - usually rounded.

6% Rock fragments - shale or silty shale, light brown to dark brown black, rounded or subrounded.

Accessory Minerals

$<$ 1% Feldspar - both twinned plagioclase and orthoclase, grains fresh to badly altered, one grain fractured, possibly by pressure,

Chlorite, Zircon, Biotite, Magnetite, Muscovite, Tourmaline, Leucoxene, Pyrite

3% Matrix - clay minerals.

2% Cement - SiO_2 as overgrowths and calcite.

1% Pore space

Classification - Quartz arenite.

Sample Number - Pembina 1-10-4-7

Location - Well Pembina 1-10, 10-1-48-8-W5
5026.5 feet below K.B. elevation

Description

Colour - medium brown-grey, oil stained.

Structure - some traces of bedding - lineation of mica flakes and of elongate quartz grains - several shale laminae.

Texture - clastic, silt to fine sand (average size 0.07 mm.), subangular to subrounded, sorting fair, well indurated.

Main Constituents

55% Quartz - grains subangular, some angular - average size 0.07 mm., thirty to forty per cent strained, few overgrowths, many long and concave contacts, may be some replacement by chlorite.

18% Chert and microquartzite - more rounded than quartz.

5% Rock fragments - mainly shale, dark brown, subrounded.

Varietal Minerals

1% Muscovite - many grains bent.

Accessory Minerals

< 1% Zircon, Leucoxene, Ilmenite, Biotite, Magnetite, Chlorite, Garnet, Pyrite, Feldspar.

15%± Matrix - clay minerals and fine silt- and clay-size quartz (amount difficult to assess since there are several shale laminae)

Cement

2% Calcite - patchy

1% SiO_2 - overgrowths

Classification - Quartz wacke.

Sample Number - St. Hudson's Bay Rat Cr. B-12-6

Location - Well Stanolind Hudson's Bay Rat Creek B-12, 16-33-48-10-W5
5784.75 feet below K.B. elevation

Description

Colour - dark grey, mottled light grey.

Structure - clean sandstone, muddy sandstone and shale, complexly interbedded; relatively sharp contacts between different rock types; clean sandstone appears cross laminated; muddy sandstone appears disturbed as if worked over by some agency; shale lineated, in one of laminae there is an isolated circular patch of sand about 2 mm. in diameter, heavily pyritized.

Texture - clastic, grains average 0.10 mm. and are subangular to subrounded, poorly sorted (in most places), well indurated.

Main Constituents

Quartz - grains subangular to subrounded, about twenty per cent are strained, about ten per cent have overgrowths, some concave and long contacts.

Chert and microquartzite

Rock fragments - argillaceous material.

Accessory Minerals

Magnetite, Muscovite, Chlorite, Tourmaline, Feldspar, Biotite, Zircon, Pyrite - disseminated.

Matrix - clay minerals and fine silt- and clay-size quartz, amount variable up to twenty per cent in sand, in shale up to ninety per cent.

Cement - calcite and SiO_2 overgrowths - trace.

Sample Number - Drayton Valley 1-12-14-5b

Location - Well Drayton Valley 1-12, 12-1-49-7-W5
4540.75 feet below K.B. elevation

Description

Colour - medium grey-brown.

Structure - clean sandstone, muddy sandstone and sandy or silty shale complexly and irregularly mixed, discontinuous lenses, no definite features discernible.

Texture - clastic, grains average 0.10 mm. and are subangular to rounded, very poorly sorted, well indurated.

Main Constituents

Quartz - grains subrounded, some grains long and thin and subangular, twenty to thirty per cent strained, some overgrowths, some concave and long contacts.

Chert and microquartzite

Rock fragments - argillaceous material.

Accessory Minerals

Muscovite, Zircon, Leucoxene, Pyrite - authigenic, Biotite, Magnetite, Feldspar.

Matrix - clay minerals (and clay-size quartz), amount variable from ten to fifty per cent, usually more than twenty-five per cent.

Cement - SiO_2 overgrowths, a trace.

Sample Number - Pembina 1-10-3-2b

Location - Well Pembina 1-10, 10-1-48-8-W5
5020 feet below K.B. elevation.

Description

Colour - medium brown.

Structure - sharp contact between clean sand and clay ironstone or sideritic mudstone - contact parallel to bedding in sandstone - ironstone massive and dense.

Texture - sandstone: clastic, very fine- to fine-grained, subangular to subrounded, sorting fair, well indurated, similar to other quartz arenites.
ironstone: chemical, microcrystalline, few clastic grains.

Main Constituents - Ironstone

85% Siderite - microcrystalline, dark brown, very high interference colours.

10% Quartz - fine sand and silt size, slightly more concentrated near contact, subangular.

5% Argillaceous material.

Main Constituents - Sandstone

60% Quartz - grains subrounded, average size 0.10 mm., some cloudy grains.

21% Chert and microquartzite

Varietal Minerals

2% Pyrite - concentrated in definite layers and appears authigenic.

APPENDIX C

Location of Samples

I. Samples for Thin-Section Study

(a) Pembina Field

Pembina 1-10, 10-1-48-8 W5

Cardium top - 4944 feet below K.B. elevation

Sample Number	Depth below K.B. elevation
P. 1-10-1-1	5011 feet
3-2a	5019.5
3-2b	5020
3-3	5020.5
4-5	5025
4-7	5026.5
5-9	5031
6-11	5034
7-13	5039
8-15	5042.5
9-16	5044.5
9-17	5046.5
10-19	5051
11-21	5055
12-23	5058.5
13-24	5060
14-26	5064.5
14-27a	5066.9
15-28	5068
17-31	5076.5

Drayton Valley 1-12, 12-1-49-7 W5

Cardium top - 4430 feet below K.B. elevation

Sample Number	Depth below K.B. elevation
D.V. 1-12-5-0	4508 feet
6-1	4510
7-2	4515.5
8-3	4517.5
9-4	4520
9-4a	4522.5
9-5	4523
11-5a	4531.75
14-5b	4540.75
16-6	4551

Stanolind Hudson's Bay Rat Creek B-12, 16-33-48-10 W5

Cardium top - 5685 feet below K.B. elevation

Sample Number	Depth below K.B. elevation
St.H.B. Rat Cr. B-12-1	5765.5 feet
2	5766.5
3	5770
4	5774.5
5	5778
6	5784.75
7	5790
8	5792
9	5797.5
10	5802.25

(b) Central Foothills Outcrops

Sample Number	Location	Stratigraphic Position
3251	South bank McLeod River, ca. ½-mile west of second bridge across river, west of Mercoal, Alta. - Location 1, Fig. 2	Lower sandstone member
3252	Same	Middle sandstone member
3253	Same	Upper sandstone member - 35 feet below top
3254	Same	Upper sandstone member - 20 feet below top
2952a	Bighorn River, Alta. Location 3, Fig. 2	Lower sandstone member - 20 feet above base
2953	Same	Lower sandstone member, 100 feet above base
2954	Same	Upper sandstone member, 100 feet below top of formation
2955	Same	Upper sandstone member - 20 feet below top of formation
3008	Southern tributary, Kisko Creek, Alta. - near confluence Location 4, Fig. 2	
3009	Same	
3416	Cripple Creek, just below Forestry road - Location 5, Fig.2	Basal sandstone member - 50 feet above formation
3417	Same	Upper sandstone member - 50 feet below formation top
3412	South Ram River falls, ½-mile below Forestry road bridge - Location 6, Fig. 2	Basal sandstone member - 15 feet above base
3413	Same	Middle sandstone member - 50 feet above base
3414	Same	Upper sandstone member - 250 feet above formation base
3415	Same	Top of 30 foot transition beds to Wapiabi - uppermost sandstone member

II. Samples for Mechanical and Heavy Mineral Analysis

(a) Pembina Field

(M denotes Mechanical Analysis.
All used for Heavy Mineral Analysis)

Pembina 1-10

Sample Number	Depth below K.B. elevation
P. 1-10 - A	5013 feet
C (M)	5021
D (M)	5025
F (M)	5030
G (M)	5033
H (M)	5037
I (M)	5041
J (M)	5045
K	5047
L	5054
M	5057
N	5062
O	5066
P	5067
Q	5070
R	5076

Drayton Valley 1-12

Sample Number	Depth below K.B. elevation
D.V. 1-12 - A_o	4509.5 feet
A (M)	4510
B (M)	4515.5
C (M)	4517
D (M)	4522.2
E	4526
F (M)	4529
G	4532.4
H	4539.5
I	4542
J	4545.2
K	4550

Stanolind Hudson's Bay Rat Creek B-12

Sample Number	Depth below K.B. elevation
Rat Creek - B (M)	5769.75 feet
C (M)	5774.25
D (M)	5777
E (M)	5782
F (M)	5789.75
G (M)	5794
H	5798.75
I	5802

(b) Central Foothills Outcrops

As for thin section study, except numbers 3008, 3009 not analysed for heavy minerals.

III. Samples for Clay Analysis

Sample Number	Location	Stratigraphic Position
T.S. Big. 173-183'	Chungo Creek, Alta. 7-43-17 W5 - Location 2, Fig. 2	Silty shale collected from 173 feet to 183 feet above formation base

Also numbers 2954, P. 1-10-A, C. K, R - locations previously given.

IV. Samples for Photographs

Sample Number	Depth below K.B. elevation
P. 1-10 - B	5019.5 feet
E	5026
K_1	5049
N_1	5065.5

Locations of all other samples given previously.

APPENDIX D

Description of Plates

Plate 1

Photomicrographs of Heavy Minerals

Figure 1 Zircon - Pembina 1-10-M - well-rounded, turbid, medium grey, anhedral, 230x.

Figure 2 Zircon - Pembina 1-10-H - subangular, colourless, subhedral rod, terminations well developed at one end only, 230x.

Figure 3 Zircon - Rat Creek B - subrounded, medium grey, subhedral rod, terminations at one end only, 230x.

Figure 4 Zircon - Rat Creek B - angular, colourless, anhedral, irregularly fractured, 300x.

Figure 5 Zircon - Pembina 1-10-M - subangular, dark grey, subhedral rod, one end fractured, 650x.

Figure 6 Zircon - Pembina 1-10-M - rounded, dark grey, 650x.

Figure 7 Zircon - Rat Creek B - subrounded, dark grey, subhedral, one end fractured, inclusions parallel to c-axis, 650x.

Figure 8 Zircon - Drayton Valley 1-12-K - rounded, light grey, subhedral, zoned, 230x.

Figure 9 Zircon - Rat Creek B - subangular, colourless, subhedral, both ends fractured, 300x.

Figure 10 Zircon - Pembina 1-10-J - subangular, colourless, subhedral rod, one end fractured, globular inclusion at one end, 300x.

Figure 11 Zircon - Drayton Valley 1-12-K - angular, colourless, euhedral, one end fractured, inclusion parallel to c-axis, 230x.

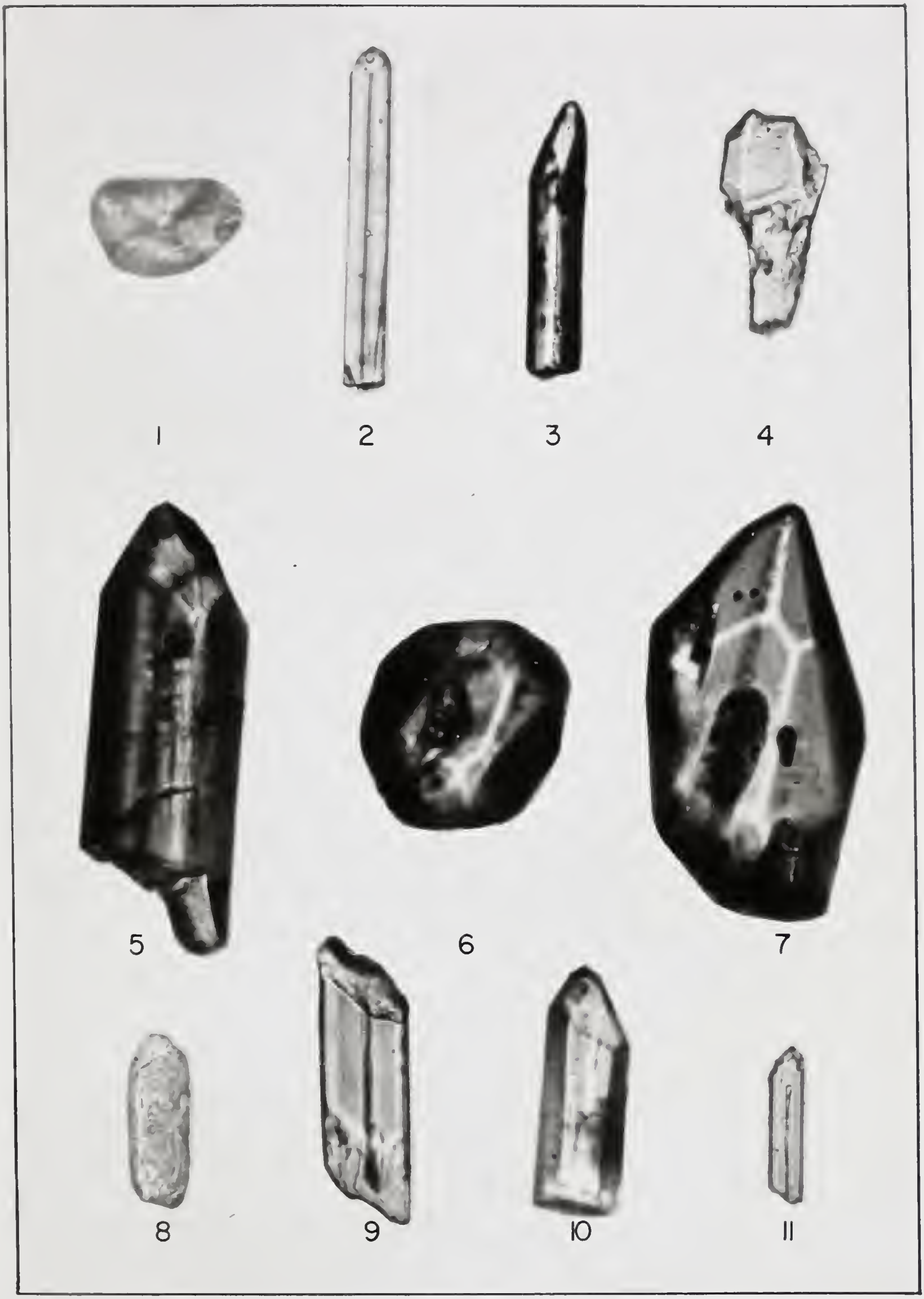


PLATE I.

Description of Plates

Plate 2

Photomicrographs of Heavy Minerals

Figure 1 — Apatite - Pembina 1-10-H - rounded, dark purple core, colourless about edges, subhedral, numerous rod-like inclusions (fractures?) parallel to and perpendicular to the c-axis, numerous dusty inclusions (iron-oxide?), 300x.

Figure 2 — Apatite - Rat Creek B - subrounded, colourless, anhedral, dust-like inclusions, 450x.

Figure 3 — Apatite - Drayton Valley 1-12-K - subangular, colourless, euhedral prism, few dust-like inclusions, 230x.

Figure 4 — Apatite - Pembina 1-10-H - rounded, colourless edges about purple core, subhedral, rod-like inclusions parallel to c-axis, numerous dust-like inclusions (iron-oxide?), 300x.

Figure 5 — Garnet - Drayton Valley 1-12-A - subangular, very slightly pink, normal detrital, overgrowths?, 270x.

Figure 6 — Garnet - Drayton Valley 1-12-H - subangular, colourless, detrital, surface pitted and marked (etched?), 450x.

Figure 7 — Garnet - Pembina 1-10-H - angular, colourless, etched, 450x.

Figure 8 — Garnet - Pembina 1-10-H - angular, colourless, etched, 450x.

Figure 9 — Unidentified (Cassiterite?) - Drayton Valley 1-12-H - subrounded, medium brownish-yellow, subhedral, prismatic, 450x.

Figure 10 — Unidentified (Cassiterite?) - Drayton Valley 1-12-A - subangular, dark brownish-greenish-yellow, striations across prism face, 300x.

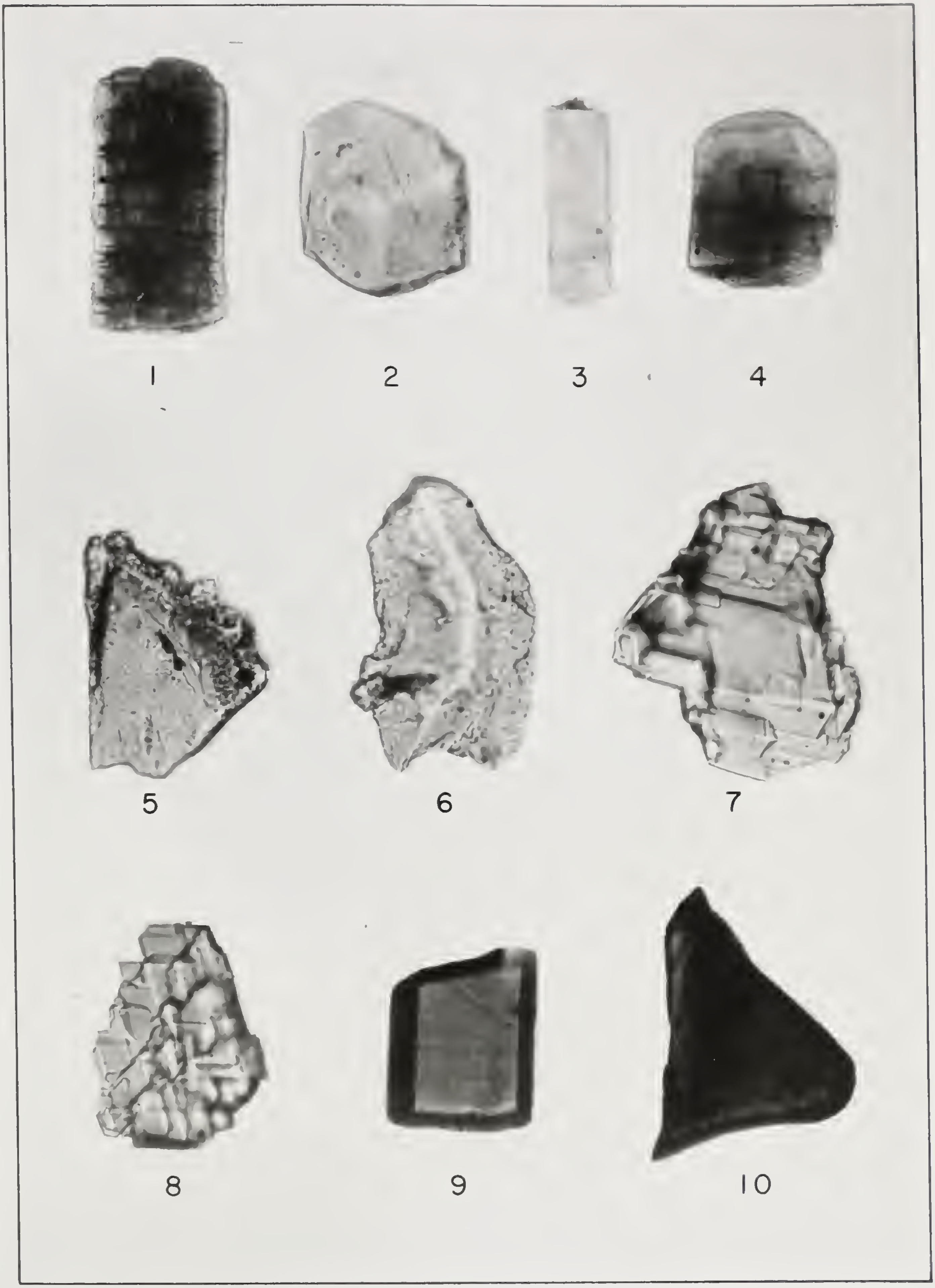


PLATE 2.

Description of Plates

Plate 3

Photomicrographs of Heavy Minerals

Figure 1	Hornblende - Pembina 1-10-H - subangular, dark green, subhedral, inclusion parallel to c-axis, 300x.
Figure 2	Zoisite - Rat Creek B - rounded, colourless, 300x.
Figure 3	Diopside - Pembina 1-10-H - subrounded, light bluish-green, needle-like inclusions, 300x.
Figure 4	Tourmaline - Pembina 1-10-H - rounded, colourless, subhedral, prismatic, zoned, inclusions, 450x.
Figure 5	Tourmaline - Pembina 1-10-H - subrounded, colourless, inclusion, 450x.
Figure 6	Tourmaline - Pembina 1-10-H - as Fig. 5, turned 90° to show dark brown dichroism, 450x.
Figure 7	Tourmaline - Pembina 1-10-H - rounded, dark brown, subhedral, prismatic, 450x.
Figure 8	Tourmaline - Drayton Valley 1-12-J - subangular, colourless, subhedral, prismatic, 230x.
Figure 9	Chloritoid - Pembina 1-10-H - subrounded, medium greenish-blue, numerous carbonaceous inclusions, 300x.
Figure 10	Chloritoid - Pembina 1-10-H - subrounded, dark bluish-green, very numerous carbonaceous inclusions, 300x.

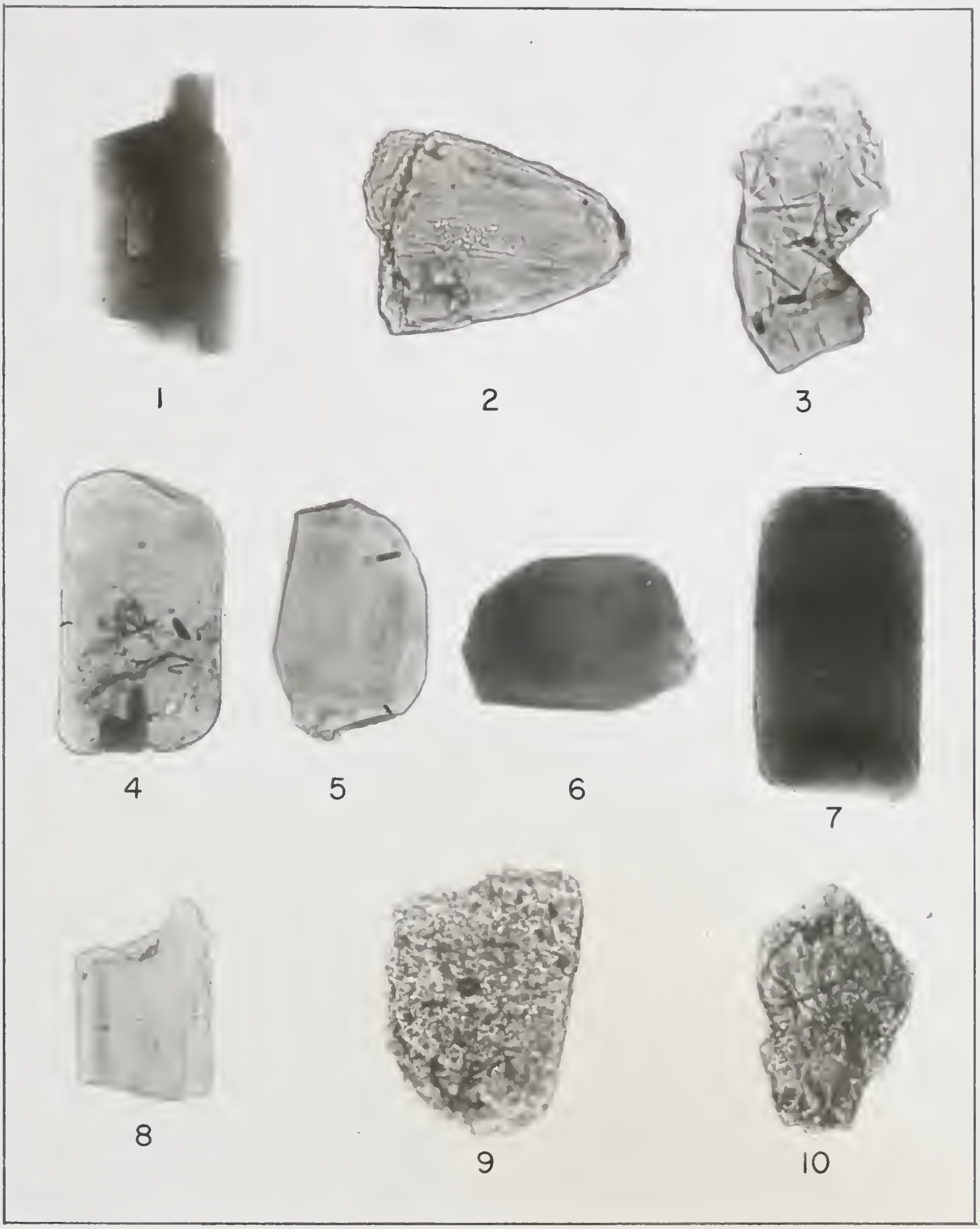


PLATE 3.

Description of Plates

Plate 4

Photomicrographs of Heavy Minerals

Figure 1 Corundum - Pembina 1-10-A - subangular, very light blue, anhedral, 450x.

Figure 2 Corundum - Pembina 1-10-A - angular, very light blue, anhedral, carbonaceous inclusions, 450x.

Figure 3 Volcanic Glass - Drayton Valley 1-12-A - angular, medium olive brown, very fresh, 230x.

Figure 4 Rutile - Rat Creek B - rounded, dark reddish-brown, 300x.

Figure 5 Rutile - Pembina 1-10-J - subrounded, dark yellow-brown, subhedral, knee-twin, striations parallel to twin plane, 450x.

Figure 6 Rutile - Rat Creek B - subangular, medium yellow-brown, anhedral, 300x.

Figure 7 Spinel - Pembina 1-10-H - subrounded, very dark brown-red, 300x.

Figure 8 Spinel - Pembina 1-10-H - subrounded, dark brown-red, conchoidal fractures, 450x.

Figure 9 Siderite - Pembina 1-10-H - rounded, medium brown, anhedral, 300x.

PLATE 4.

Description of Plates

Plate 5

Photomicrographs of Heavy Minerals

Figure 1	Garnet - #2953 - subangular, colourless, anhedral, conchoidal fracture, 300x.
Figure 2	Tourmaline - #2954 - well-rounded, pleochroic dark brown, clear rounded overgrowth, 230x.
Figure 3	Rutile - #2953 - subrounded, dark yellow brown, subhedral, striations in prism face parallel to c-axis, 450x.
Figure 4	Apatite - #2953 - subrounded, colourless, anhedral, 300x.
Figure 5	Zircon - #2953 - rounded, medium grey, subhedral, mineral inclusion parallel to c-axis, 450x.
Figure 6	Tourmaline - #2954 - rounded, medium greenish-brown, subhedral, inclusions parallel to c-axis, 300x.
Figure 7	Tourmaline - #2954 - well-rounded, dark brown, 300x.
Figure 8	Apatite - #2953 - subrounded, colourless, anhedral, inclusions, 300x.
Figure 9	Epidote - #3414 - subrounded, medium green, anhedral, conchoidal fracture, 230x.
Figure 10	Zircon - #2955 - very well-rounded, dark grey, inclusions, 450x.
Figure 11	Siderite - #2955 - subangular, colourless, anhedral, inclusions, 300x.

PLATE 5.

Description of Plates

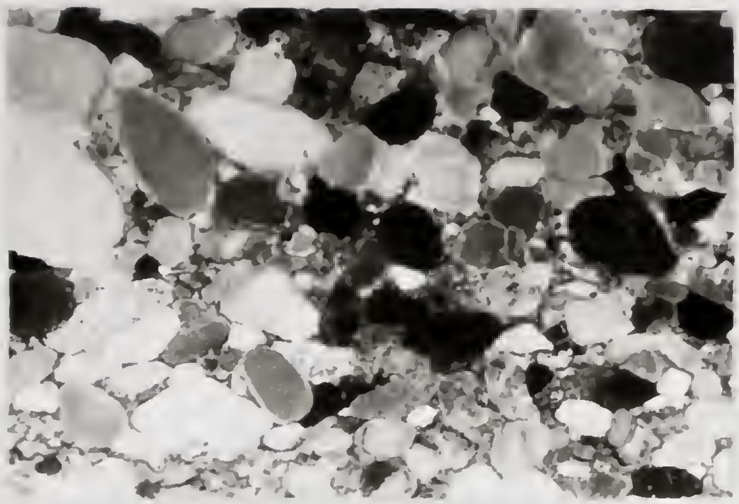
Plate 6

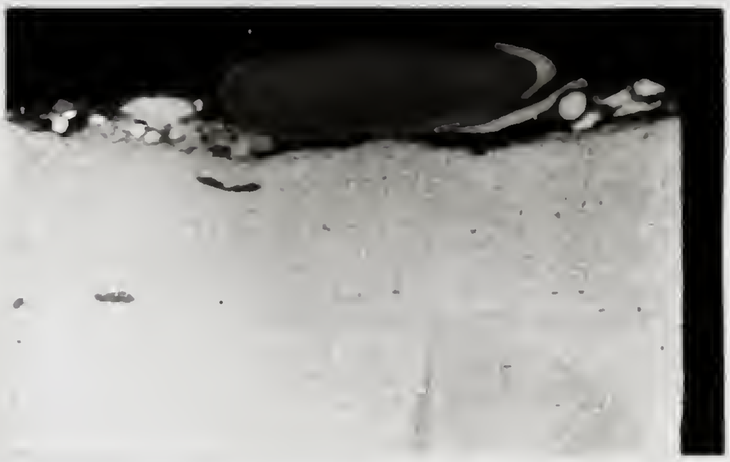
Photographs of Core

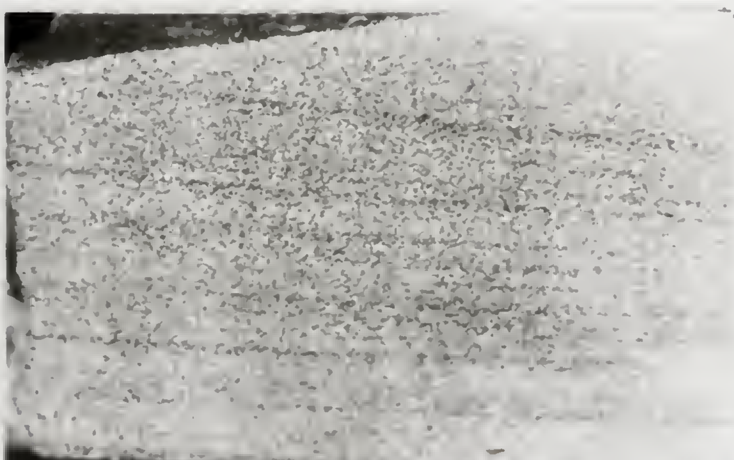
Figure 1 Conglomerate - Pembina 1-10-2a - well-rounded, varicoloured chert and quartz pebbles, fairly well sorted, average size about one-quarter inch in diameter, note concave contacts between some pebbles, sand matrix, 2x.

Figure 2 Conglomerate-Sandstone contact - Rat Creek B-12-2 - sharp (disconformable?) contact between conglomerate unit and upper sandstone unit, surface of sandstone appears eroded or scoured. Conglomerate: well-rounded, varicoloured chert pebbles set in black shale matrix, large pebble in centre is clay ironstone nodule. Sandstone: light brown, very fine to fine grained, well sorted, some traces of bedding, dark patches are clay (shale) flakes, 1.5x.

Figure 3 Sandstone - Drayton Valley 1-12-D - dark brown, oil stained, very fine to fine grained, well sorted, very thin shale laminae, slightly speckled appearance, 2.5x.







Description of Plates

Plate 7

Photographs of Core

Figure 1 Sandstone - Rat Creek B - light brown, slightly oil stained, very fine to fine grained, well sorted, slight indications of bedding, 2x.

Figure 2 Sandstone - #3413 - light brownish grey, fine grained, no porosity, well sorted, massive, slightly speckled appearance, upper sandstone member, 2.5x.

Figure 3 Sandstone - Clay Ironstone contact - Pembina 1-10-3-2b - contact sharp, slightly uneven, two load-casts of sand into the clay ironstone. Sandstone: medium brown, oil stained, very fine to fine grained, well sorted, three sets present, top and bottom sets laminated, centre set cross-laminated. Clay ironstone: dark brown, aphanitic, hard, dense and uniform, 1.5x.

Description of Plates

Plate 8

Photographs of Core

Figure 1 Sandstone and shale - Pembina 1-10-13-24 - complexly interbedded, sandstone at top cross-laminated with animal burrow and showing load-cast at base - irregular lenses of sandstone in the shale, 1.5x.

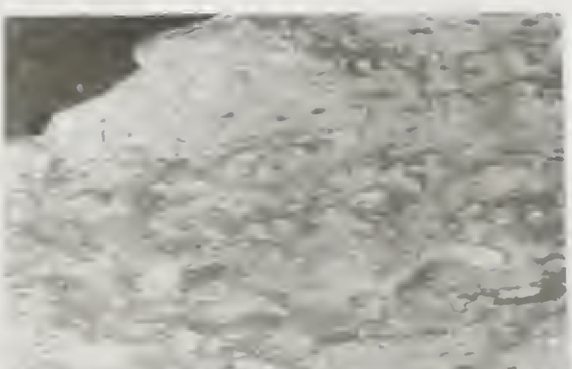
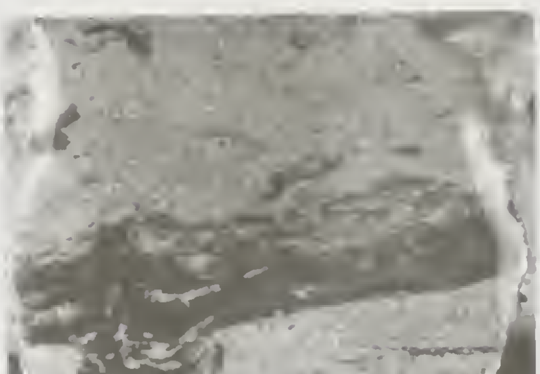
Figure 2 Sandstone and shale - Pembina 1-10-E - complexly interbedded, sandstone laminated and, in places, crumpled - load-cast at base of upper sandstone layer, white marks due to faulty film processing, 0.75x.

Figure 3 Sandstone and sandy shale - Pembina 1-10-K_1 - completely and irregularly intermixed, no semblance of bedding retained at all, 1x.

Figure 4 Sandstone and shale - Pembina 1-10-N_1 - irregularly mixed, sandstone in discontinuous lenses - more sandstone than in Pembina 1-10-K_1, 0.75x.

Figure 5 Sandstone and shale - Drayton Valley 1-12-16-6 - sandstone beds separated by shale lens, worm burrow in lower left corner, white streaks on sides due to faulty film processing, 2x.



Description of Plates

Plate 9

Thin-Section Photomicrographs

Figure 1 Drayton Valley 1-12-5-0 - fractured pebbles in the conglomerate, infilled and partially replaced by calcite cement, x nicols, 32x.

Figure 2 Pembina 1-10-3-2a - sutured (microstylolitic) contact between quartzite pebbles in conglomerate, normal light, 32x.

Figure 3 Rat Creek B-12-3 - quartz arenite, fine-grained, clean, well sorted, oil producing - light mineral, quartz; light grey, mottled mineral, chert; dark grains, rock fragments - small amount of matrix around grains, normal light, 100x.

Figure 4 Pembina 1-10-4-7 - quartz wacke, very fine-grained, less well sorted - light minerals, quartz, chert and microquartzite; dark grains, rock fragments; much matrix, normal light, 100x.

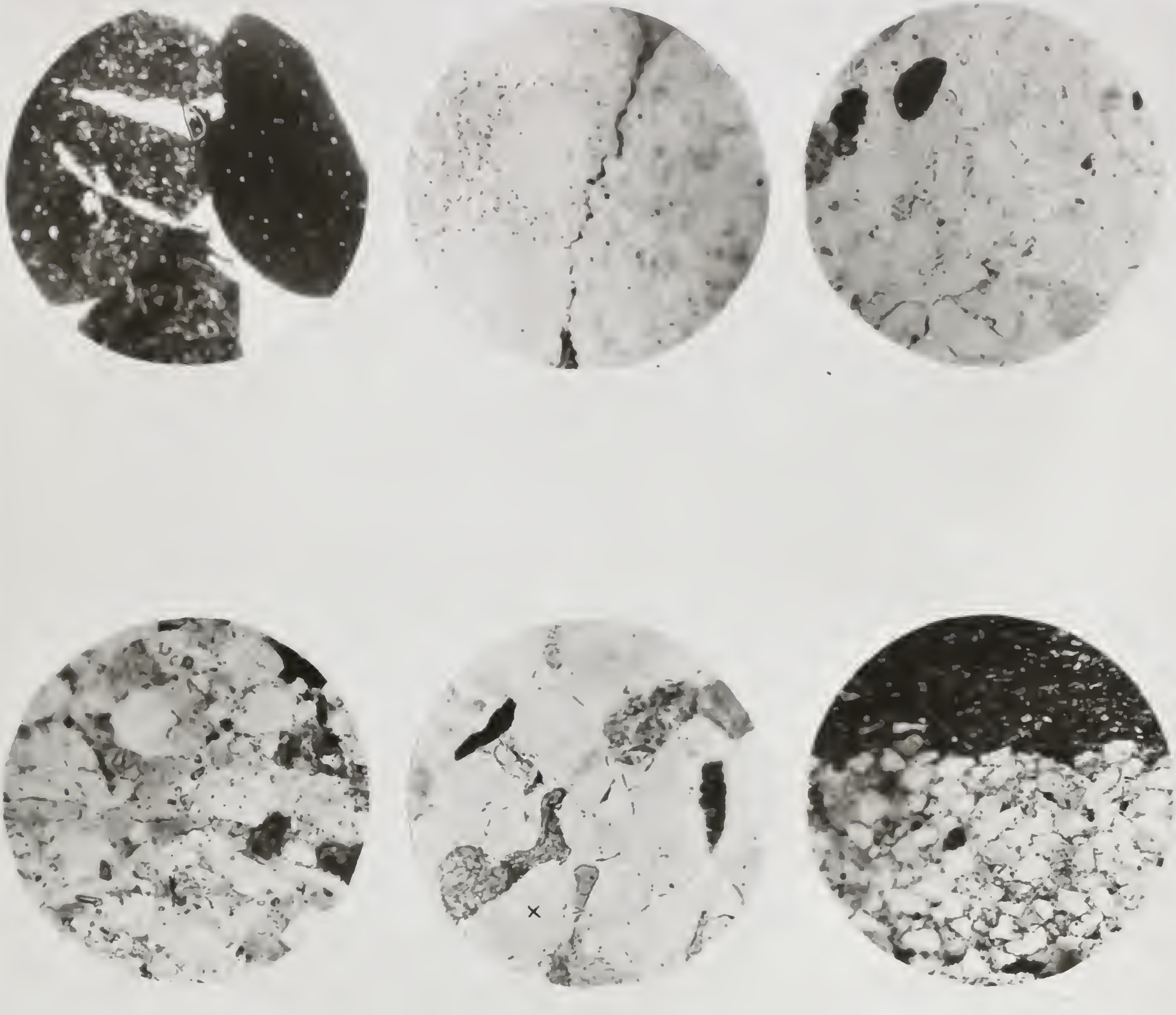
Figure 5 #2955 - quartz arenite from outcrop, medium to coarse grained, well cemented - light minerals, quartz, chert and microquartzite; dark grains, rock fragments - grain marked X shows overgrowth on rounded grain, normal light, 50x.

Figure 6 Rat Creek B-12-6 - sharp contact between relatively "clean" sandstone, lower part, and silty shale, upper part, normal light, 50x.

Figure 7 Pembina 1-10-9-16 - sharp contact between "clean" sandstone (quartz arenite), lower part, and argillaceous sandstone, upper part, normal light, 50x.

Figure 8 Drayton Valley 1-12-11-5a - argillaceous sandstone (upper part), silty shale (centre) and "clean" sandstone (lower part), with sharp contacts between, normal light, 16x.

Figure 9 Pembina 1-10-3-2b - sharp contact between quartz arenite, light, and clay ironstone (sideritic mudstone), dark, normal light, 16x.



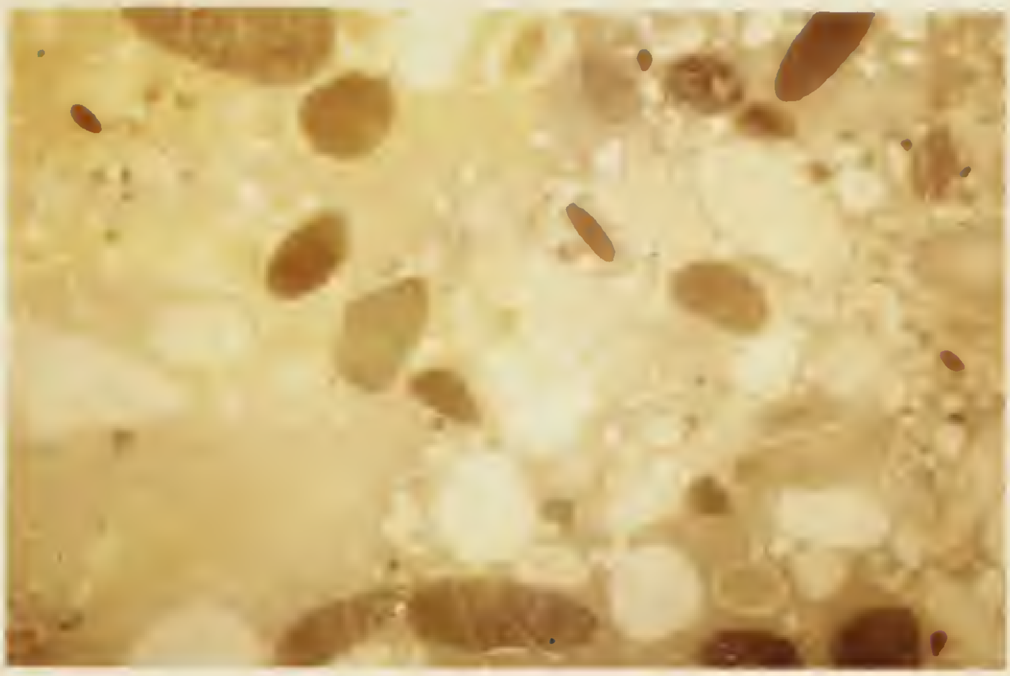
Description of Plates

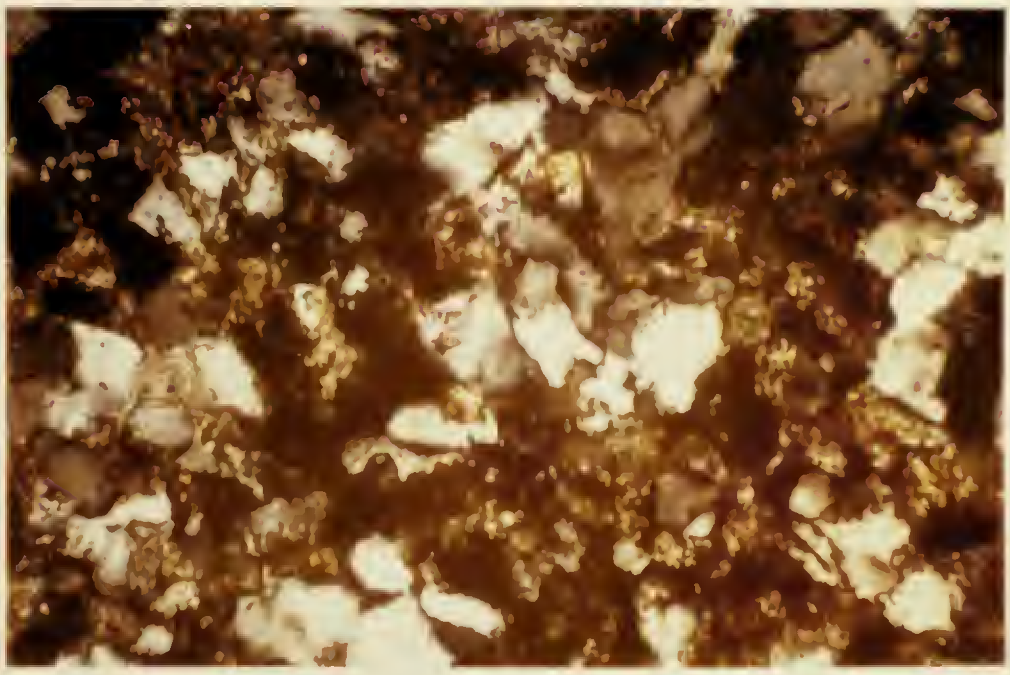
Plate 10

Colour Photographs

Figure 1 Conglomerate - Pembina 1-10-B - pebbles vari-coloured chert and quartzite, average one-quarter to one-half inch in diameter, very well rounded, some have earlier fractures healed with silica, note what appears to be a reaction rim (bleaching due to weathering?) around a few, particularly in lower right corner - matrix sideritic mudstone (light brown, aphanitic), 1x.

Figure 2 Sandstone - #3252 - poorly sorted, quartz grains (light grey to dark bluish grey) subangular, about twenty-five per cent calcite cement (material showing high refractive index), some calcite may be detrital grains, x nicols, 100x.





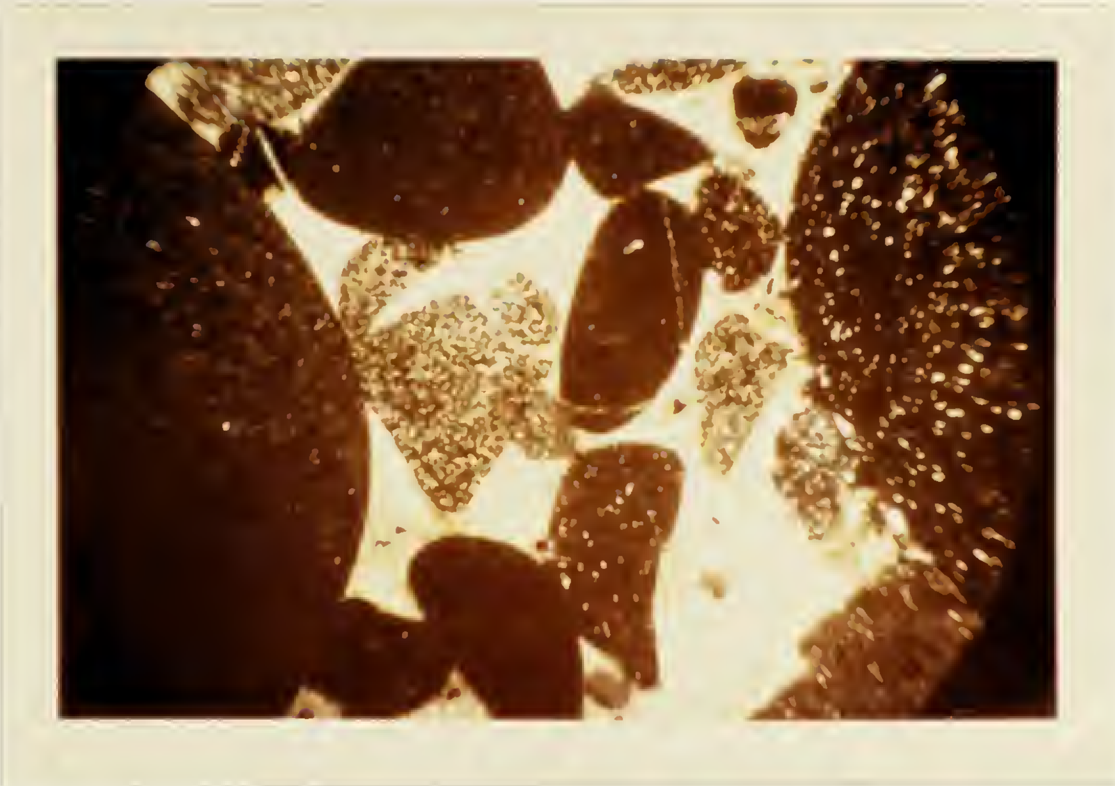
Description of Plates

Plate 11

Colour Photomicrographs

Figure 1 Conglomerate - Drayton Valley 1-12-5-0 - pebbles well-rounded (black to speckled grey) and are of chert mainly - several, e.g. one to left-centre, are fractured and fractured infilled with surrounding calcite cement (white) - note that fragments still remain very nearly in original positions, only slightly moved, x nicols, 16x.

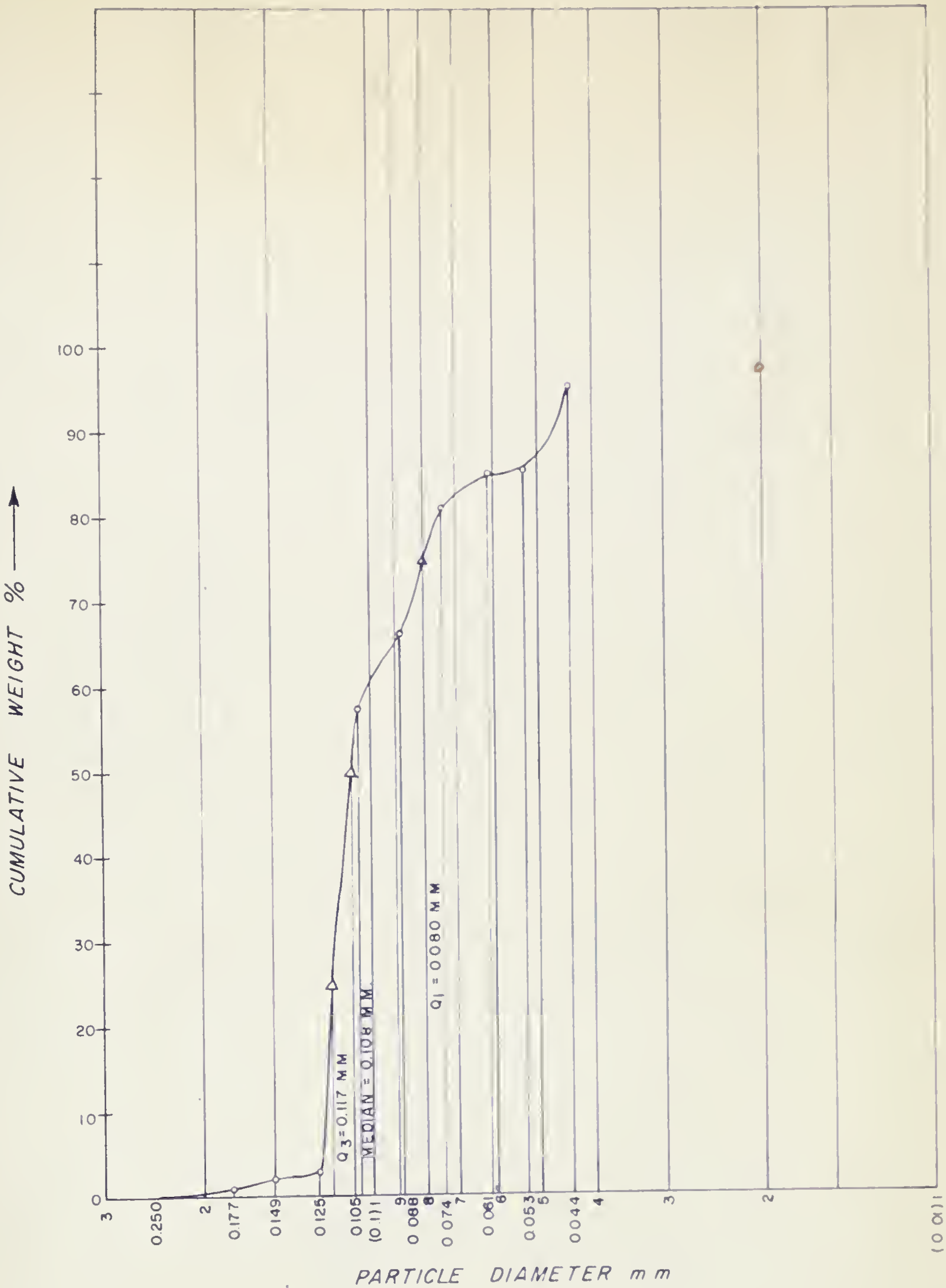
Figure 2 Conglomerate - Drayton Valley 1-12-5-0 - close-up view of different part of slide to illustrate same as mentioned above - in this case it appears as if calcite were replacing chert in pebble, as at bottom centre, x nicols, 35x.



APPENDIX E

Cumulative frequency curves from mechanical analyses of well samples.

CUMULATIVE FREQUENCY CURVE of D.V. I-12-A

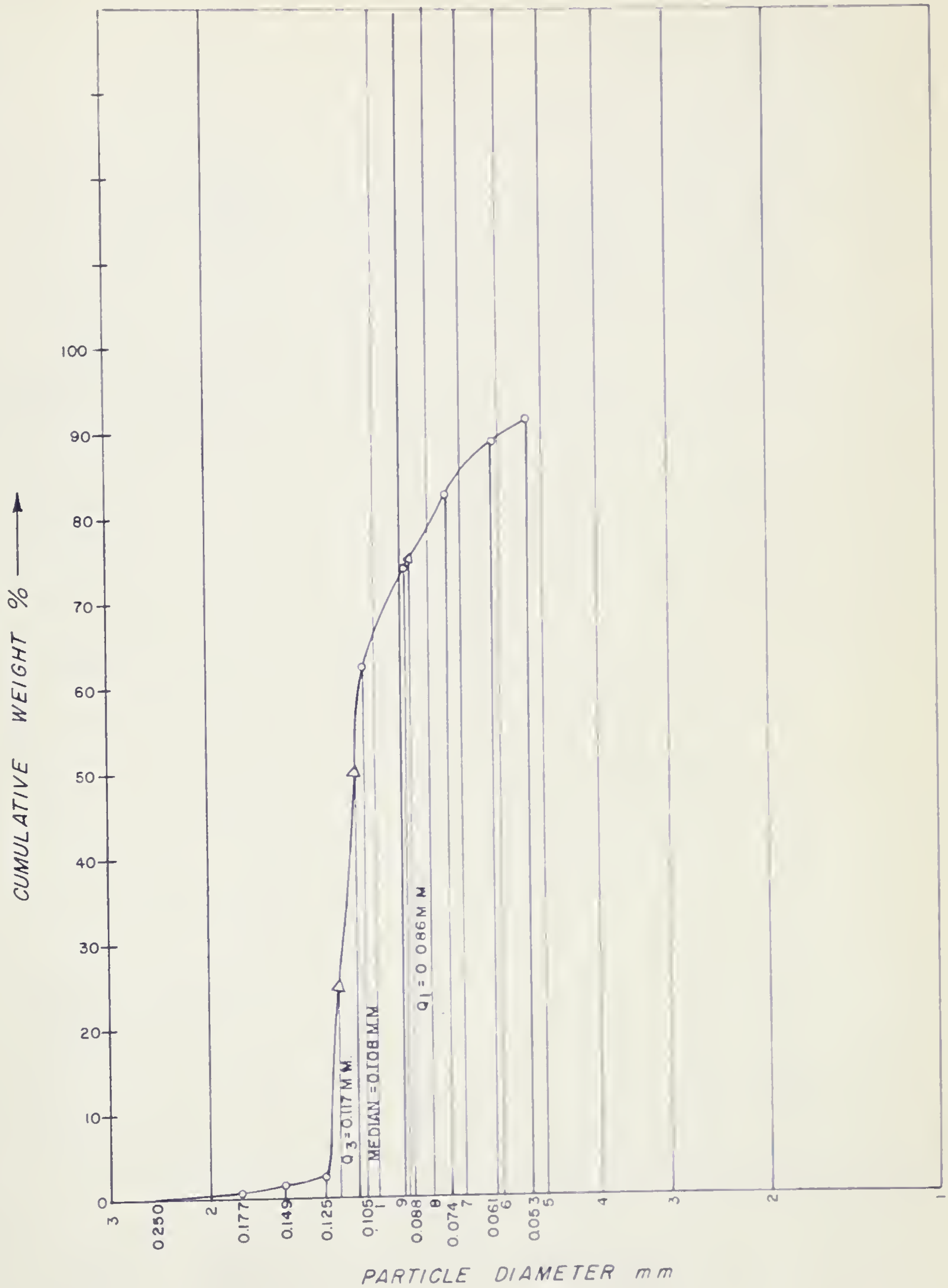


LEGEND
(for all Cumulative Frequency Curves)

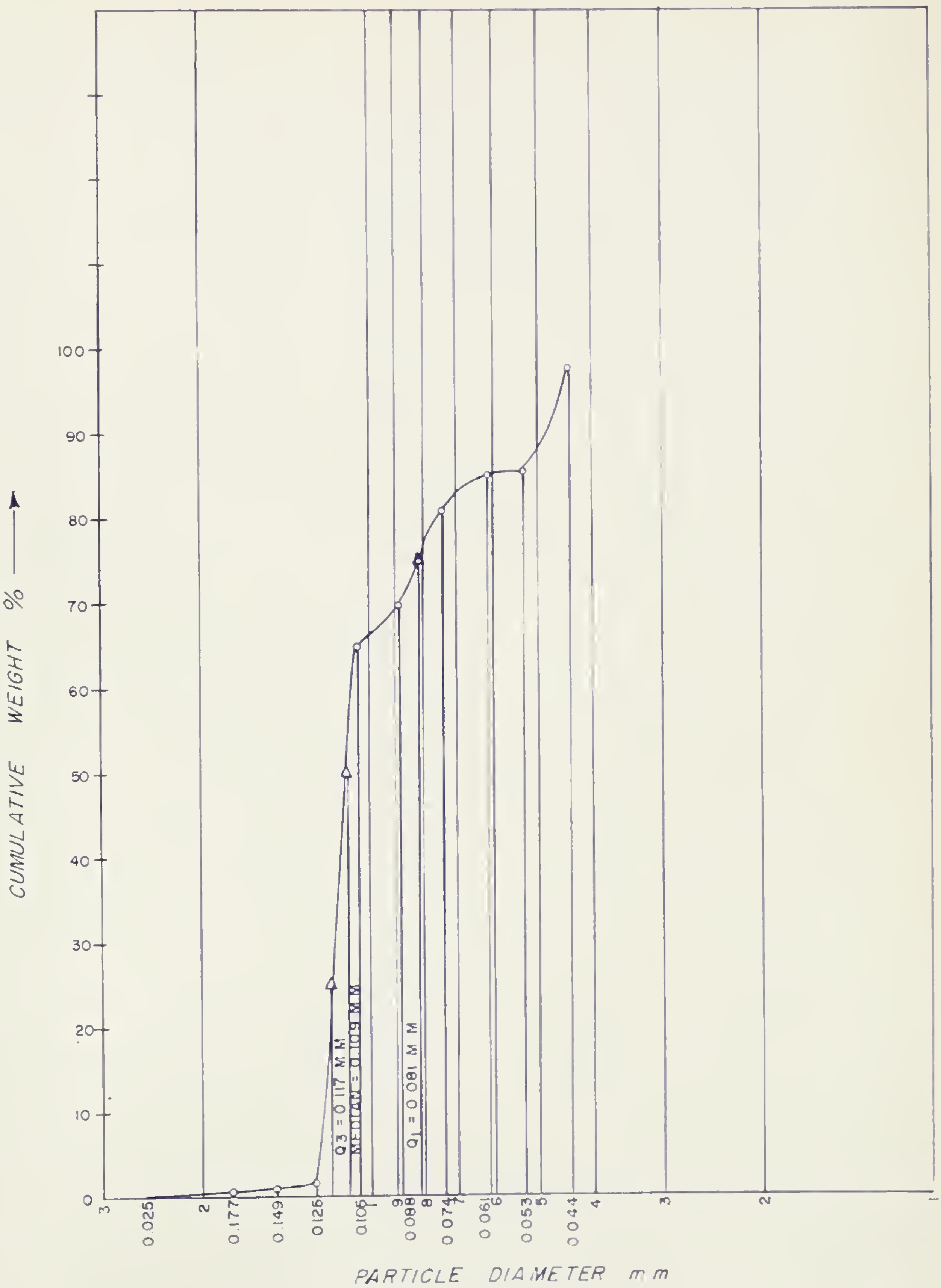
O– Measured Points

△– Position of Median and Quartiles

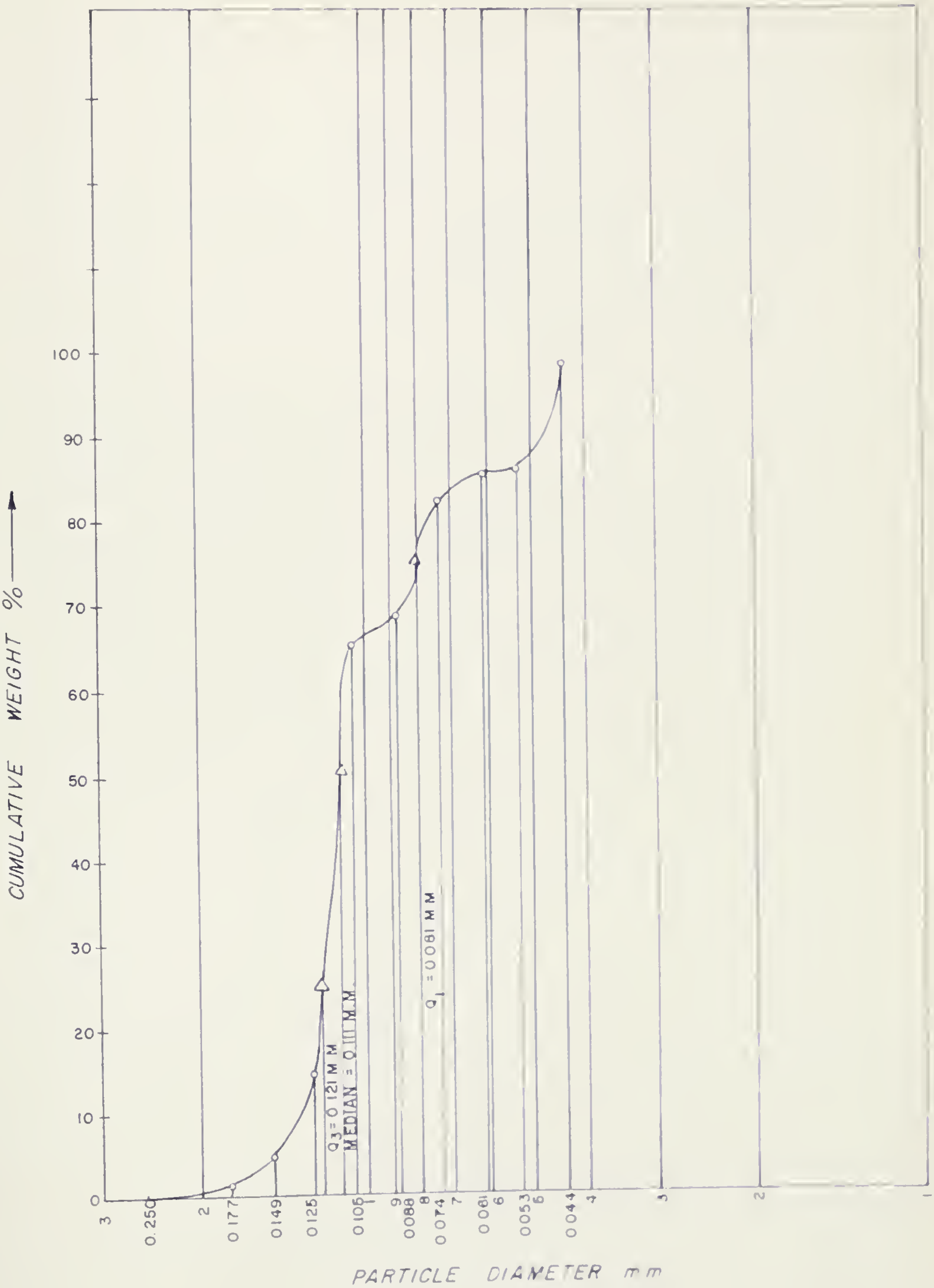
CUMULATIVE FREQUENCY CURVE D.V.1-12-B



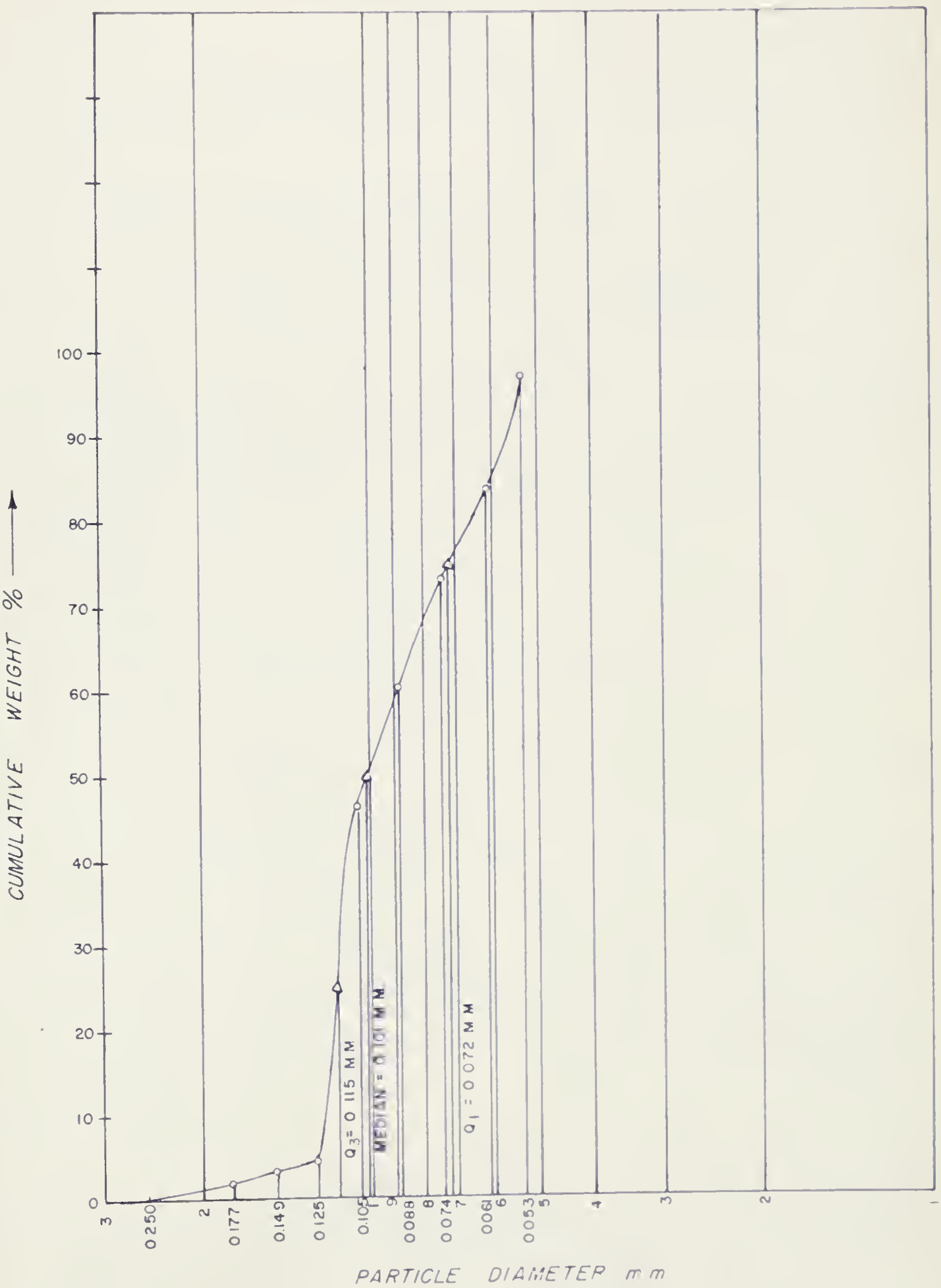
CUMULATIVE FREQUENCY CURVE D.V.1-12-C



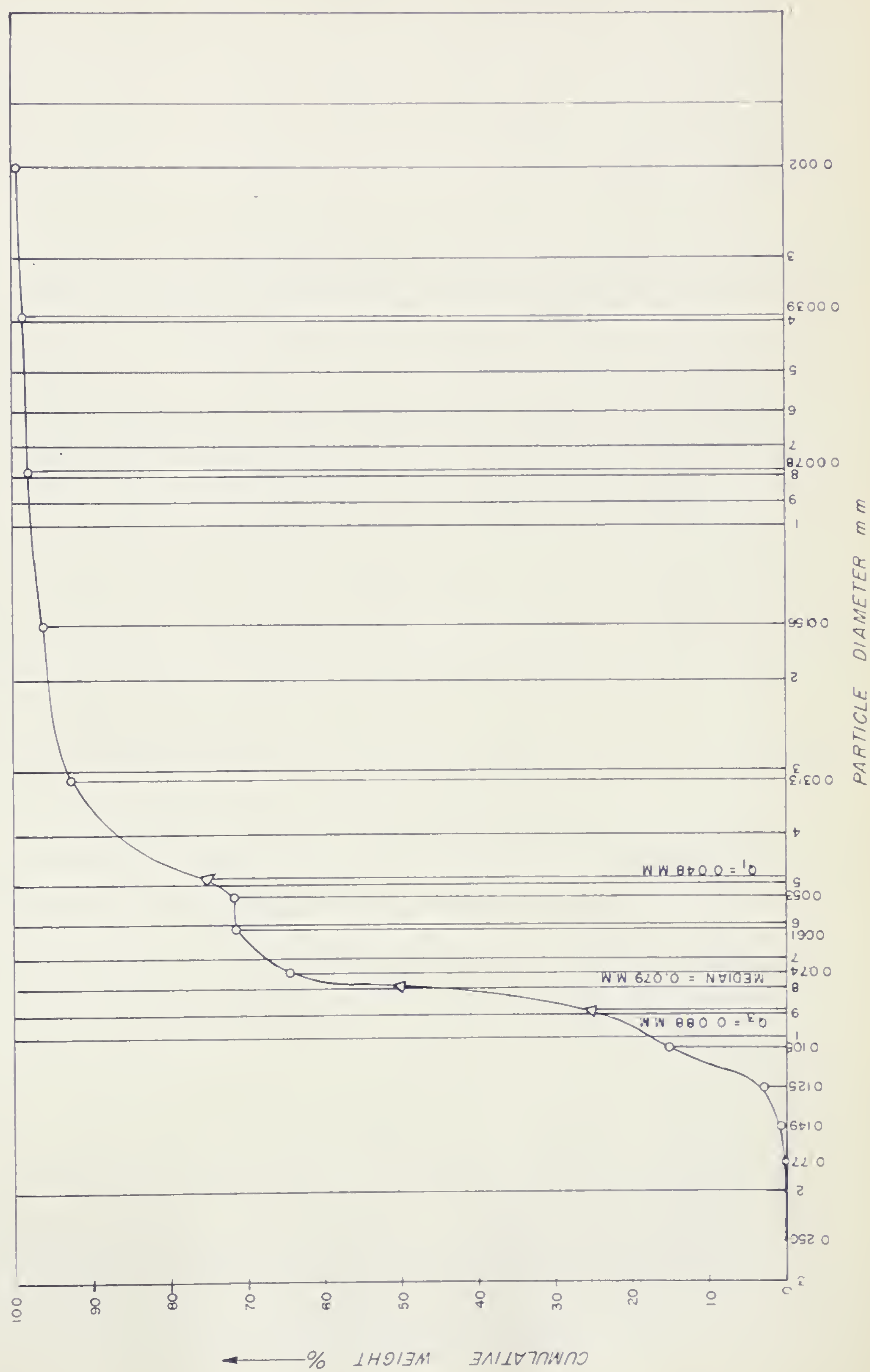
CUMULATIVE FREQUENCY CURVE D.V. I-12-D



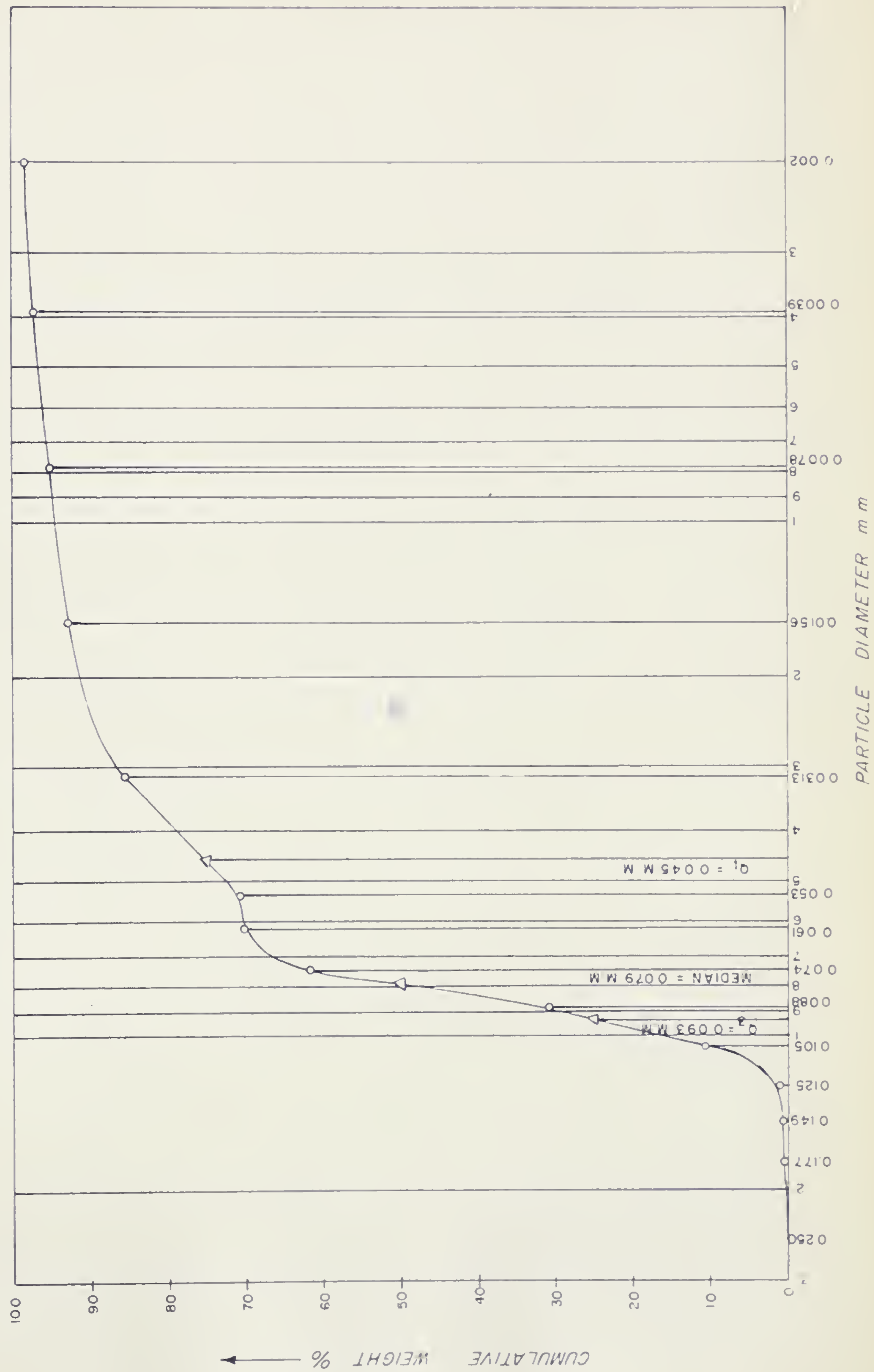
CUMULATIVE FREQUENCY CURVE D.V. 1-12-F



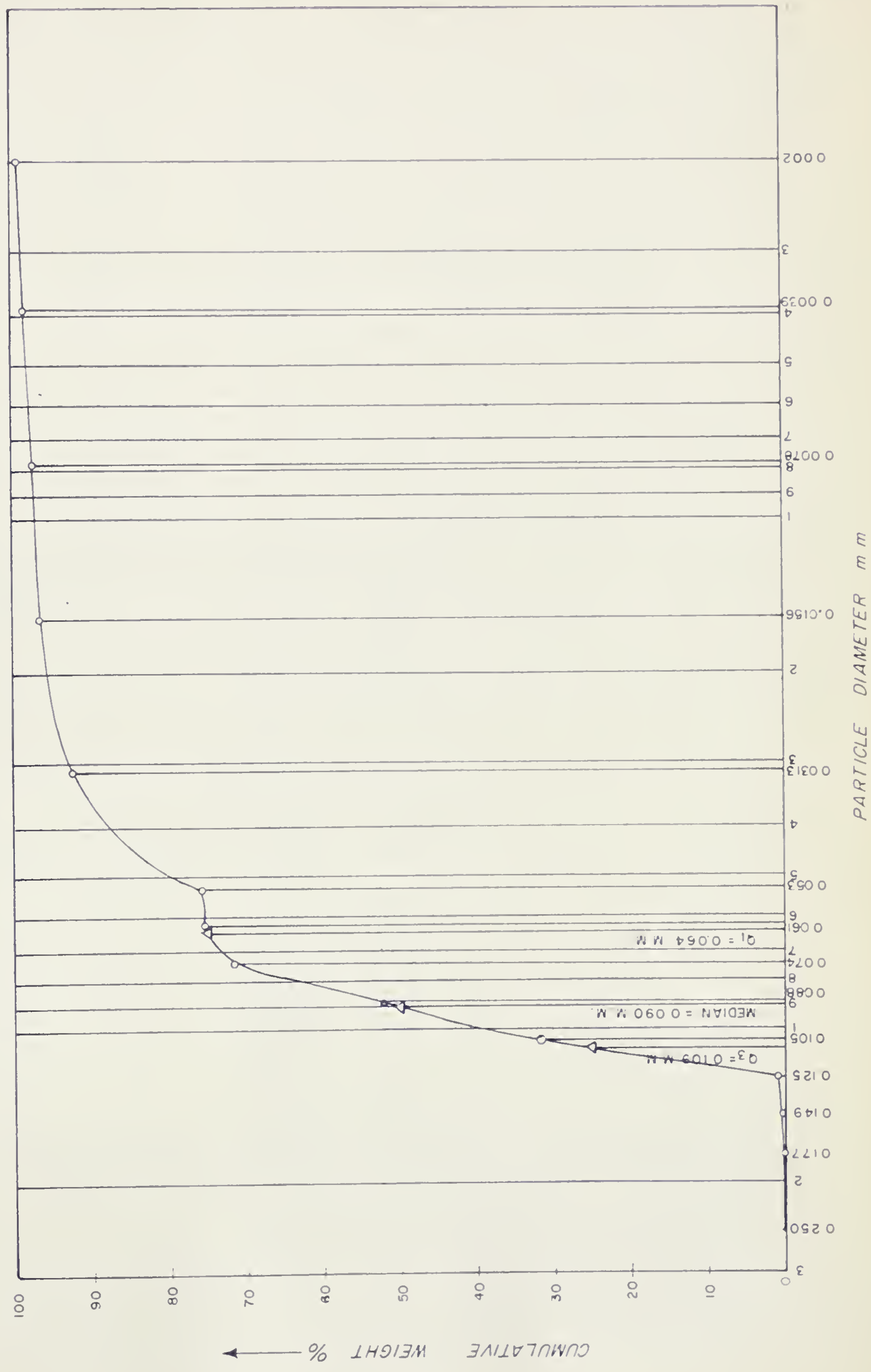
CUMULATIVE FREQUENCY CURVE of PEM. I-10-C



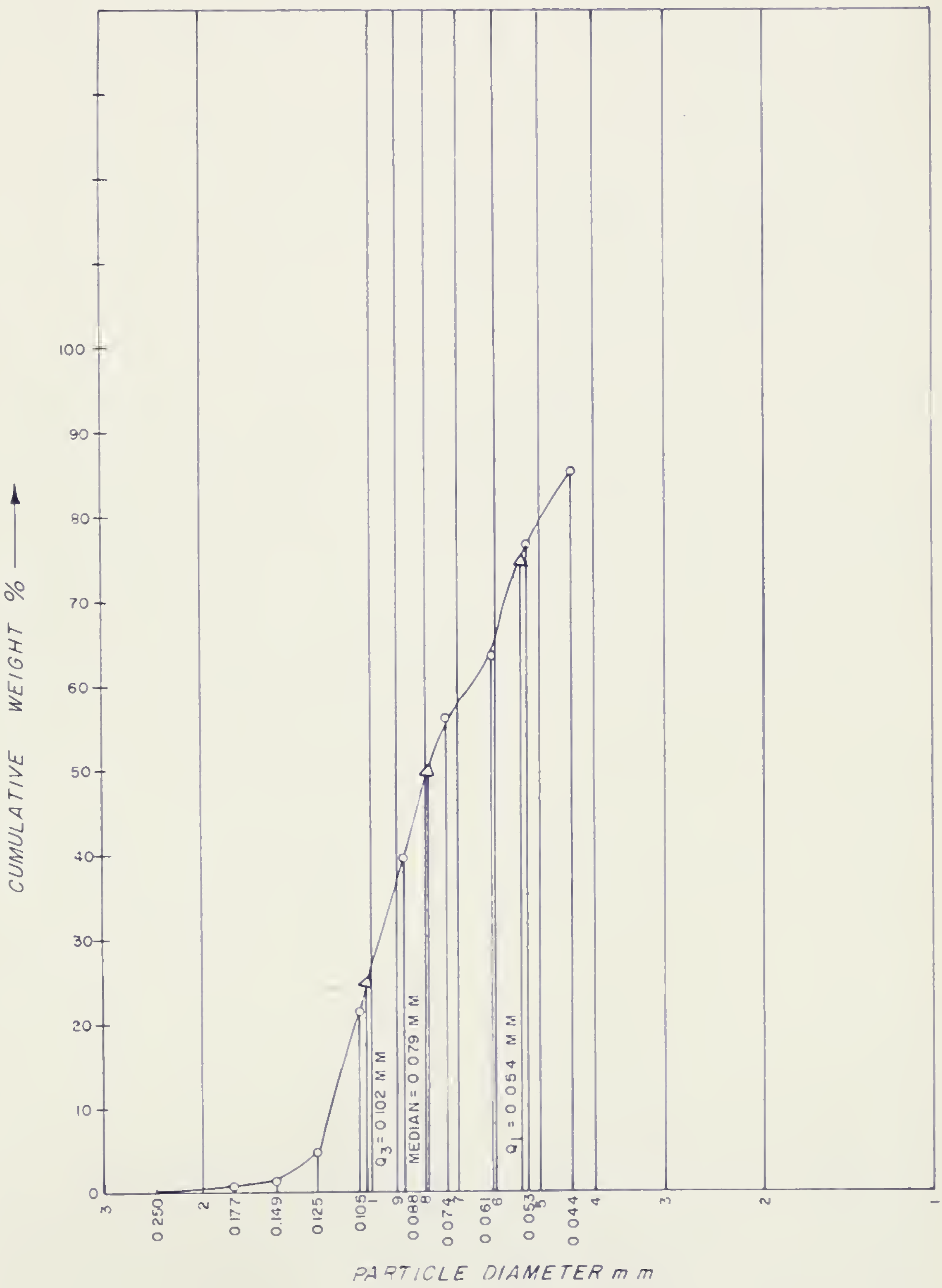
CUMULATIVE FREQUENCY CURVE of PEM. 1-10-D



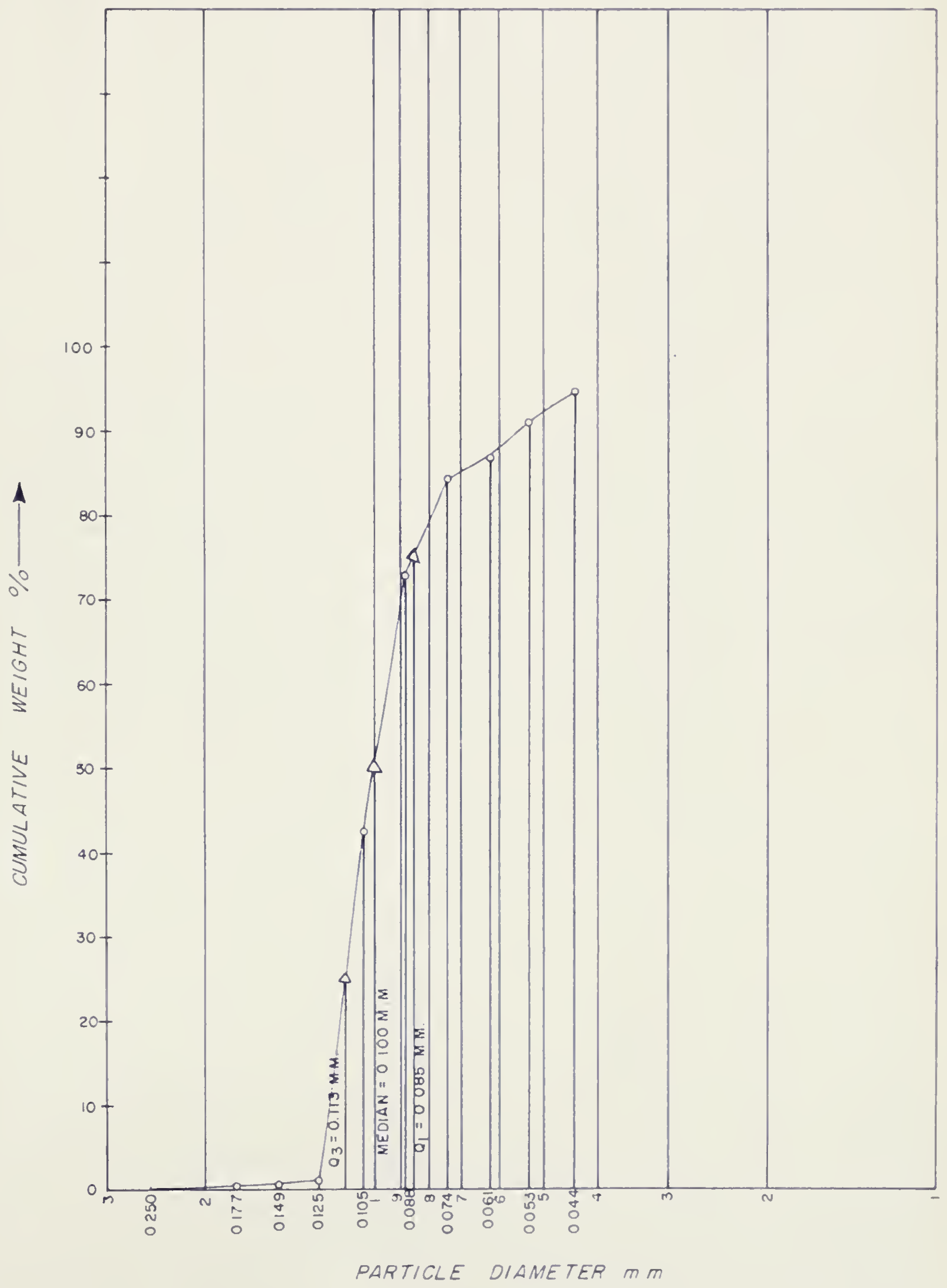
CUMULATIVE FREQUENCY CURVE of PEM. 1-10-F



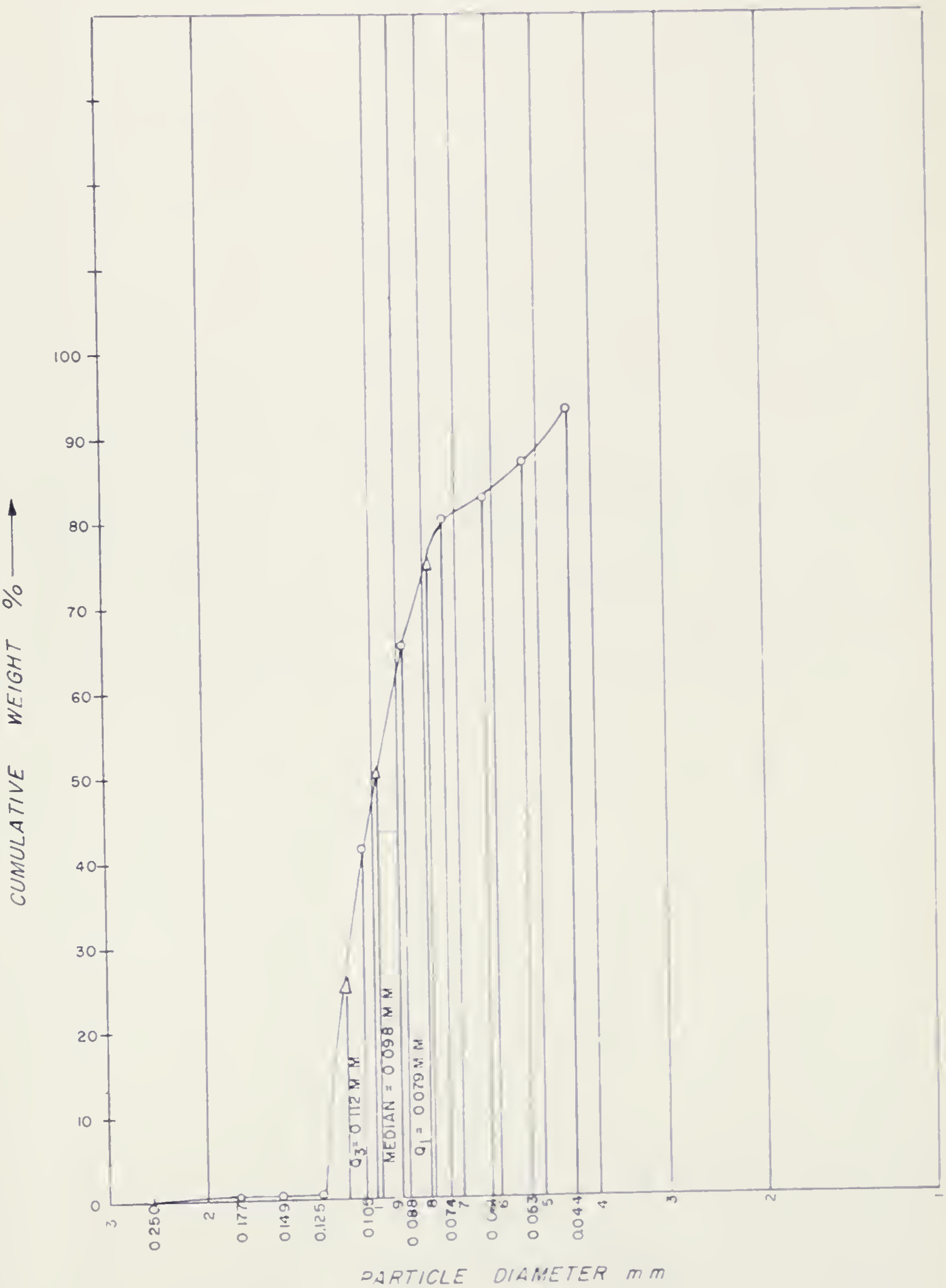
CUMULATIVE FREQUENCY CURVE of PEM. I-10-G.



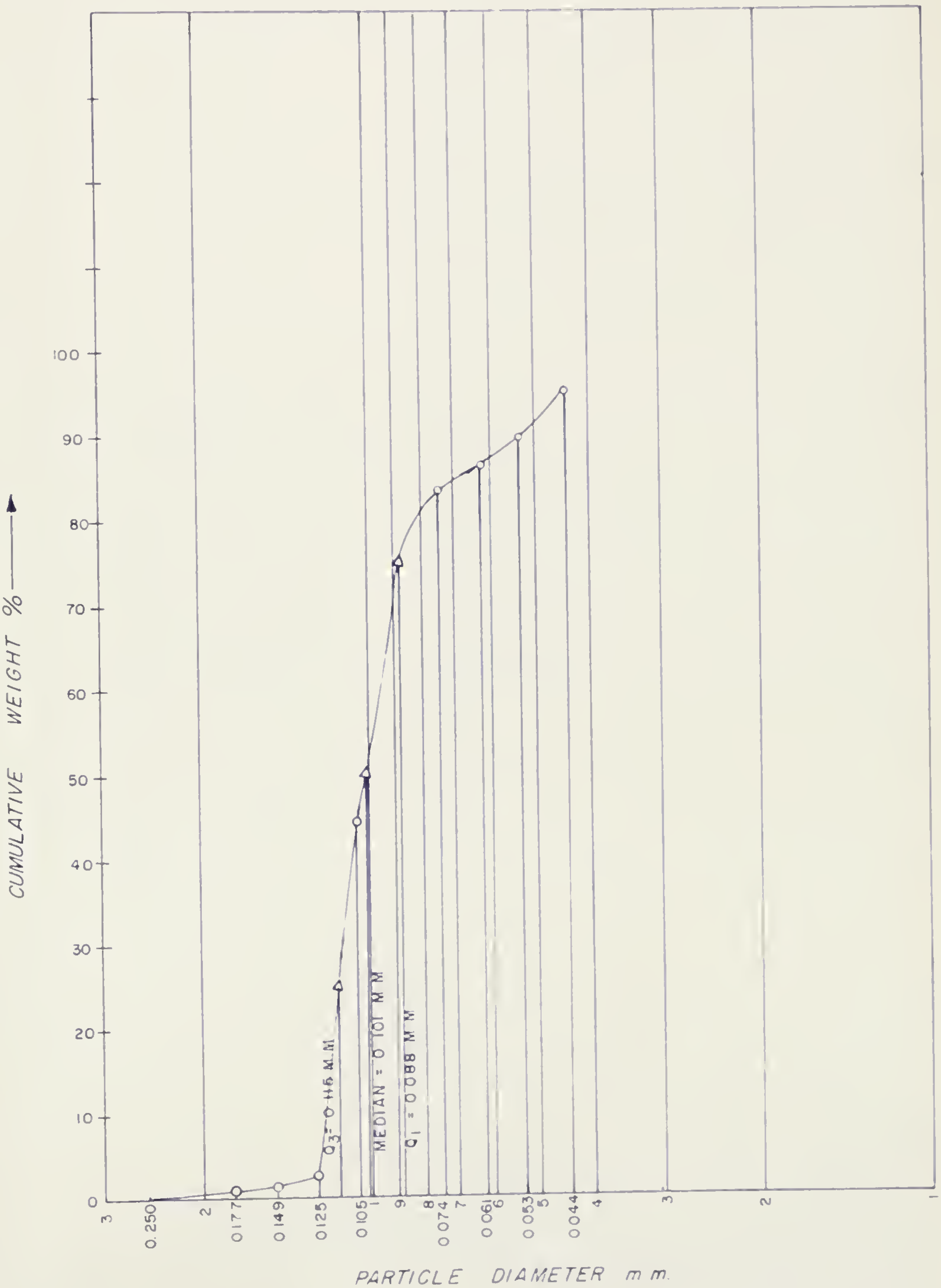
CUMULATIVE FREQUENCY CURVE of PEM. 1-10-H.



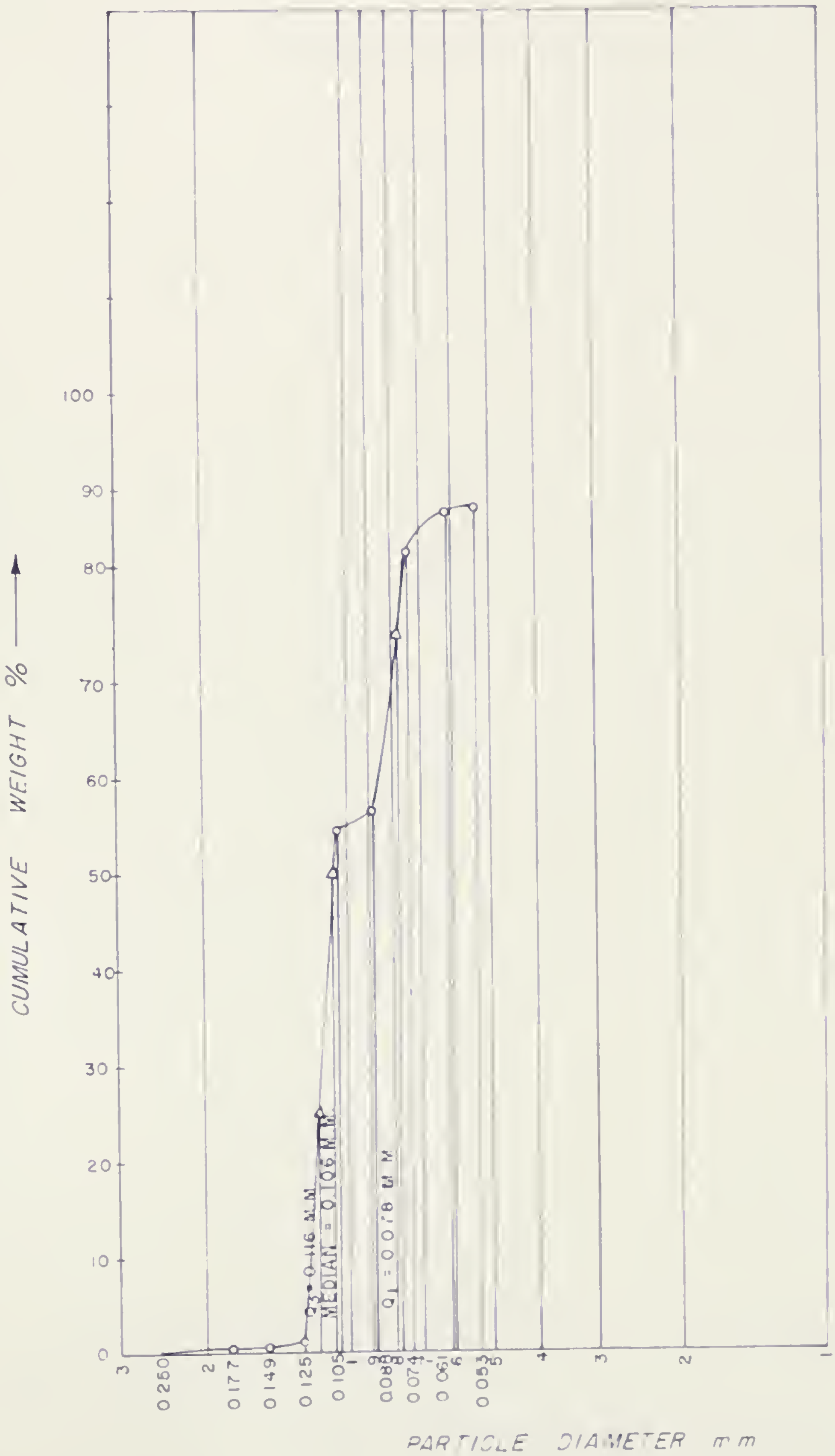
CUMULATIVE FREQUENCY CURVE of PEM. 1-10-1



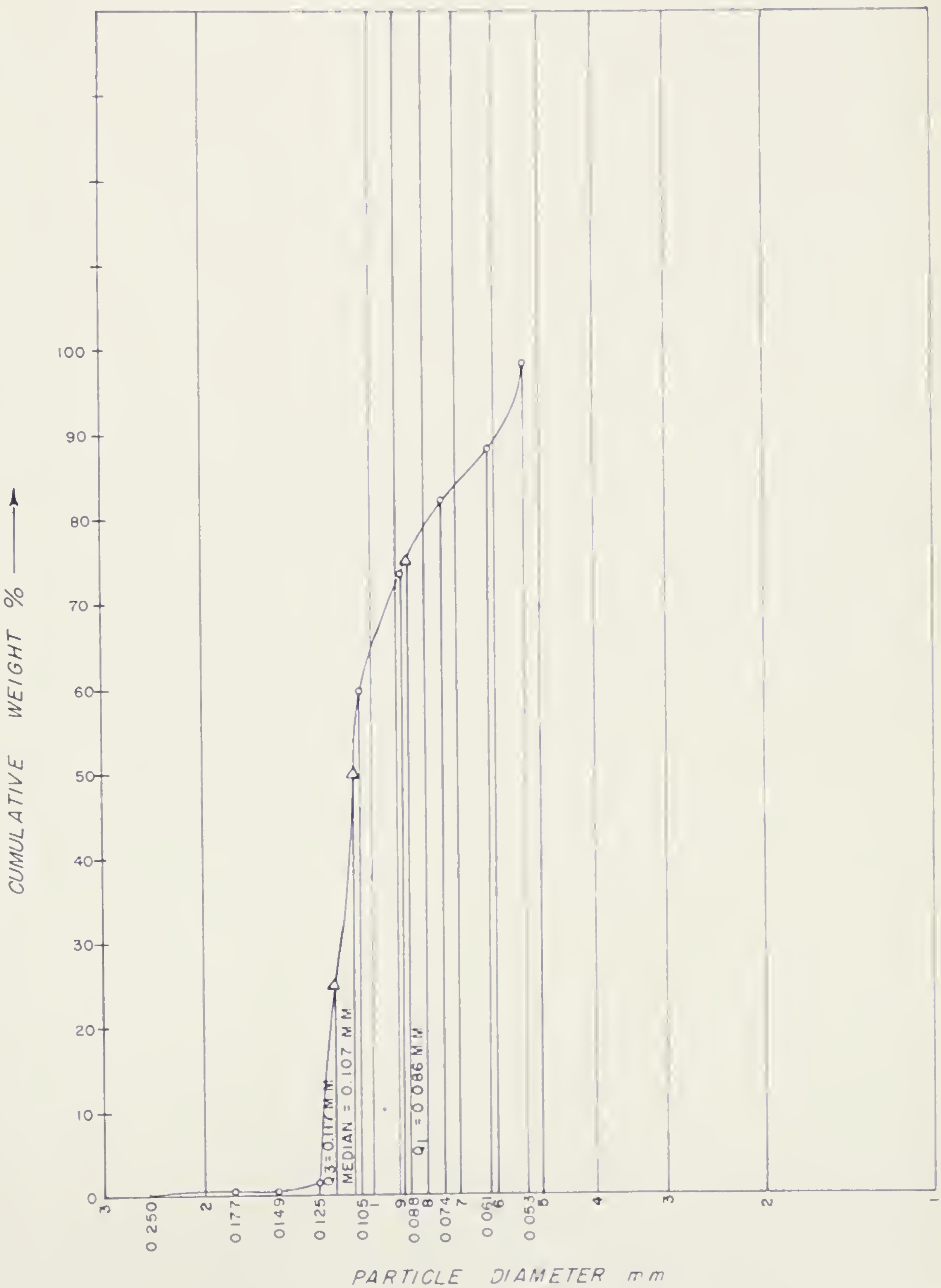
CUMULATIVE FREQUENCY CURVE of PEM. 1-10-J.



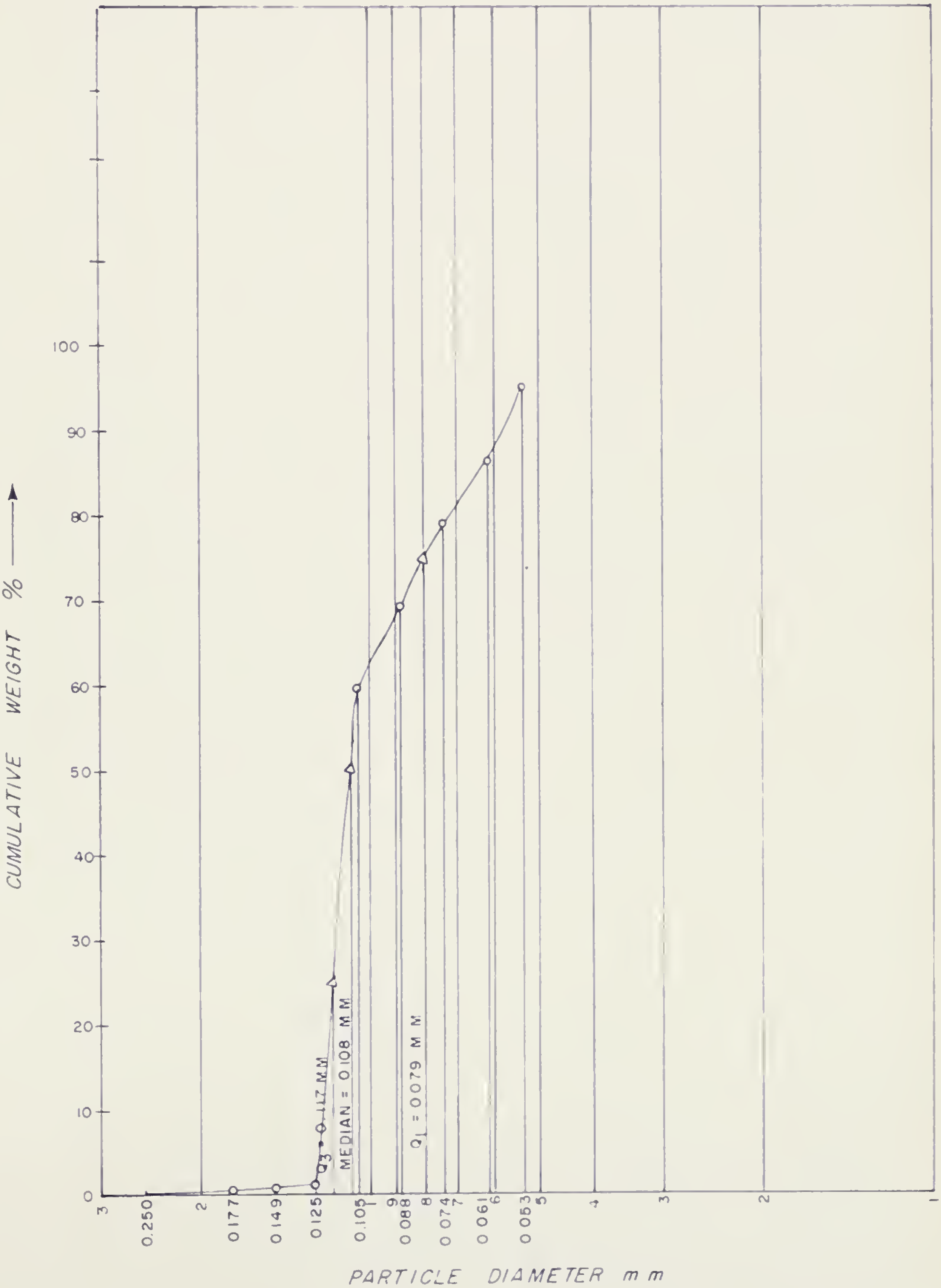
CUMULATIVE FREQUENCY CURVE of STAN. H.B. RAT CR.-B



CUMULATIVE FREQUENCY CURVE of STAN. H.B. RAT CR.-C



CUMULATIVE FREQUENCY CURVE of STAN. H.B. RAT CR.-D



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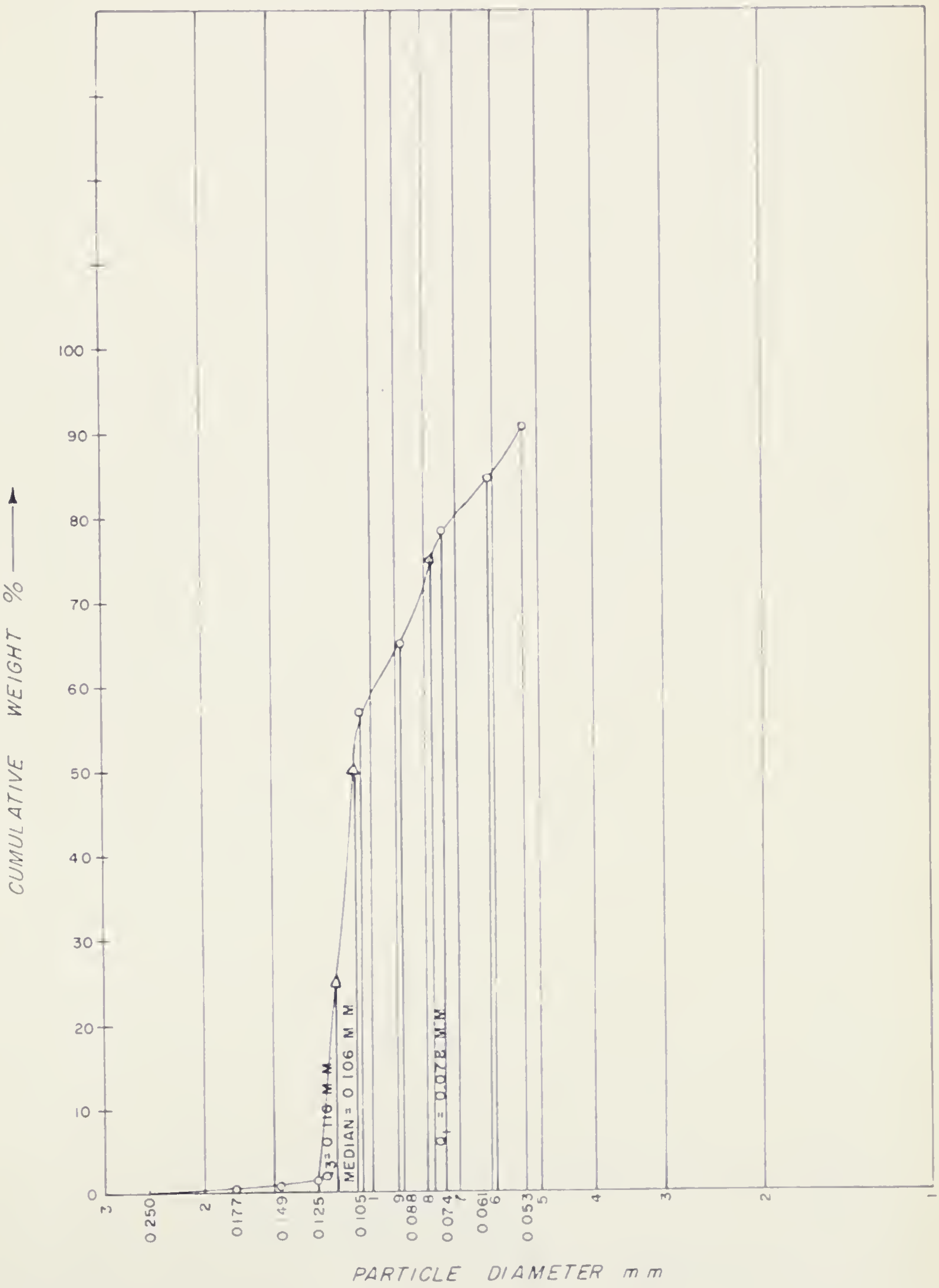

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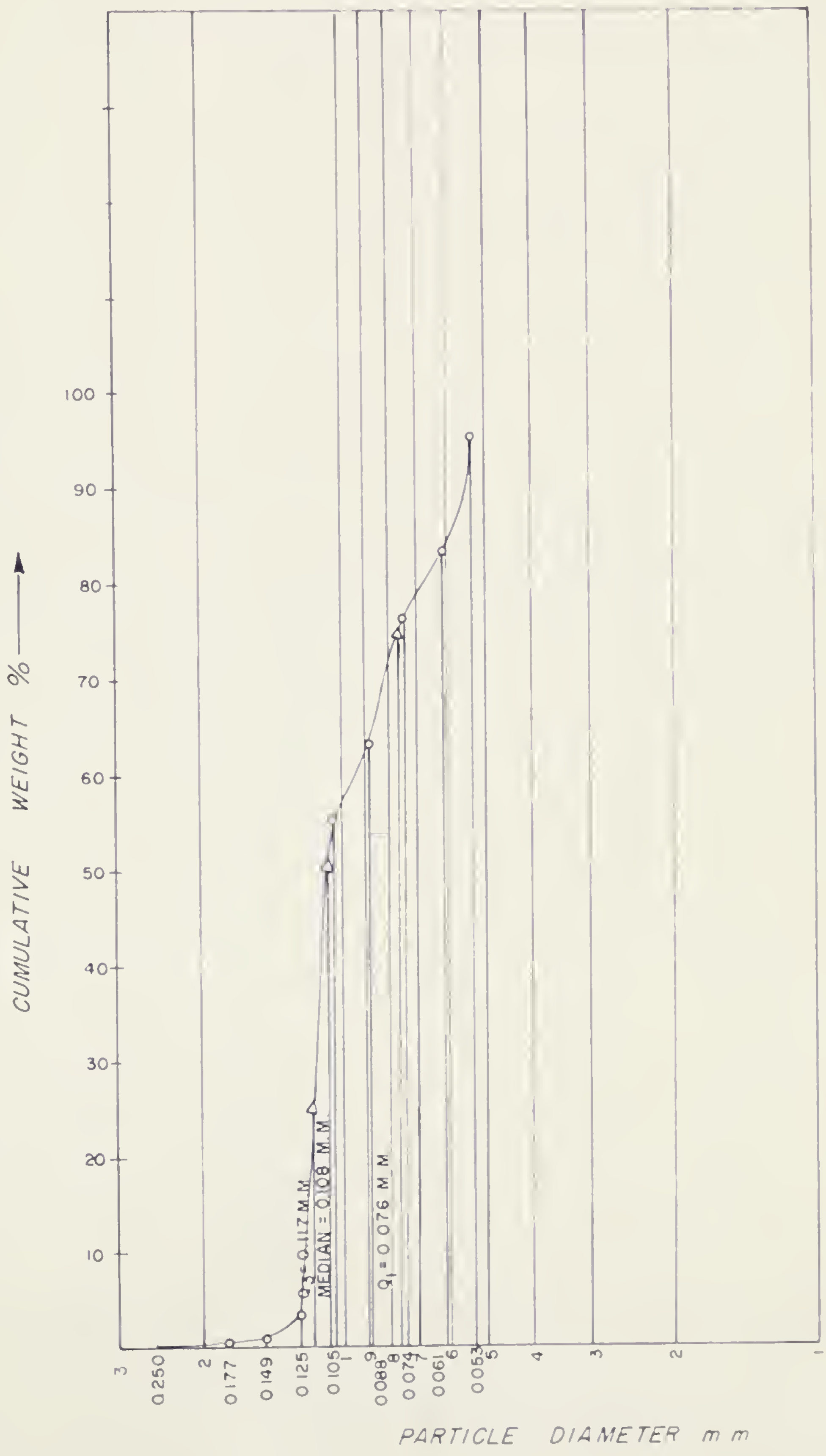

CUMULATIVE FREQUENCY CURVE of STAN. H.B. RAT CR.- G